Optics contamination in extreme ultraviolet lithography

Shannon B. Hill, N. Faradzhev, L. J. Richter, C. Tarrio, S. Grantham, R. Vest and T. Lucatorto

National Institute of Standards and Technology

Gaithersburg, MD USA

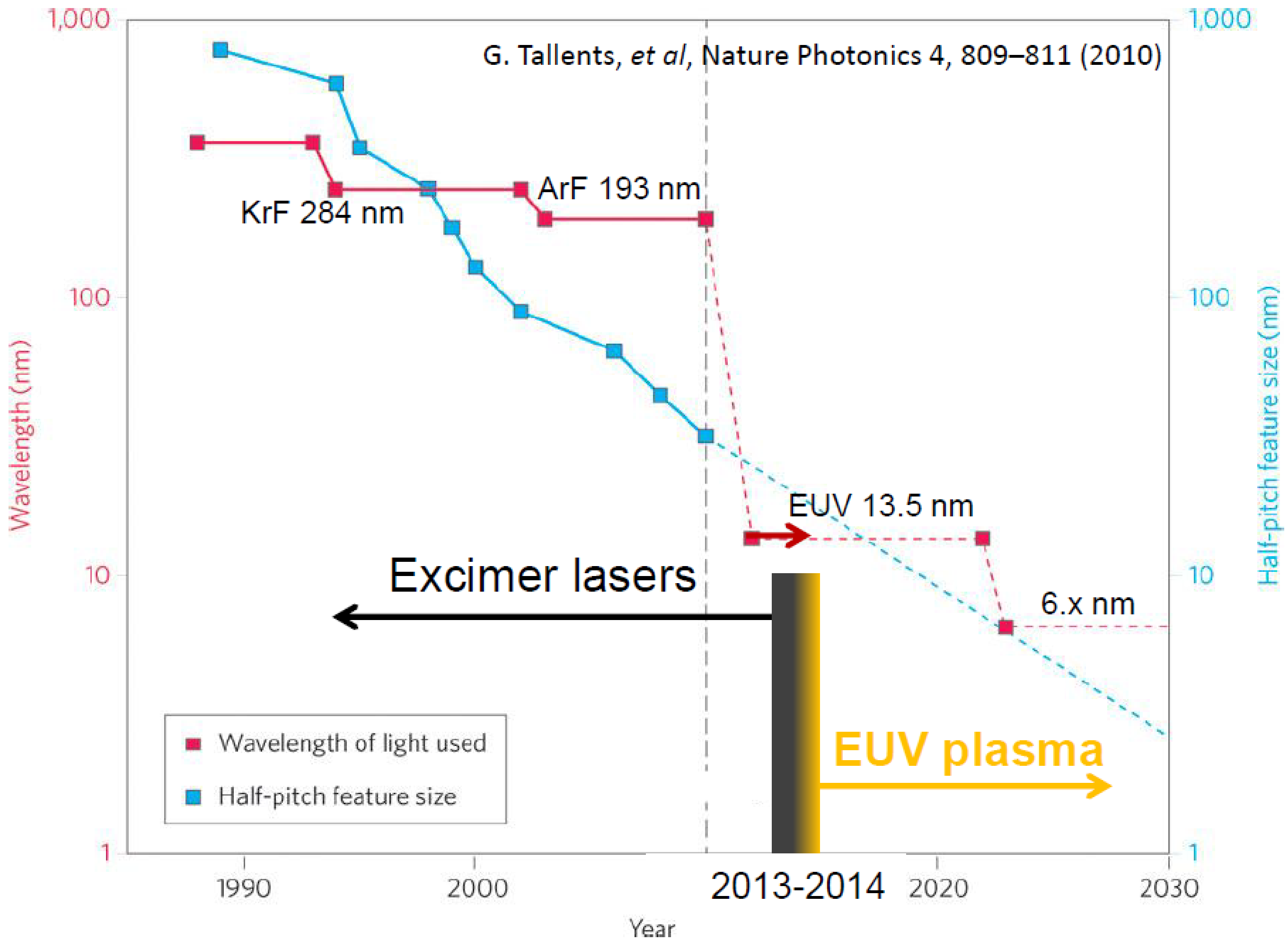
This work supported in part by Intel Corporation and ASML

NIST National Institute of Standards and Technology

Outline

- Overview of contamination in EUVL
- Pressure & species dependence of contamination
- Irradiance ("Intensity" [mW/mm^2]) dependence
- Wavelength dependence of C growth & loss
  - Secondary electrons vs. primary photons
  - Wavelength dependence of throughput loss
- In situ ellipsometric monitor of contamination

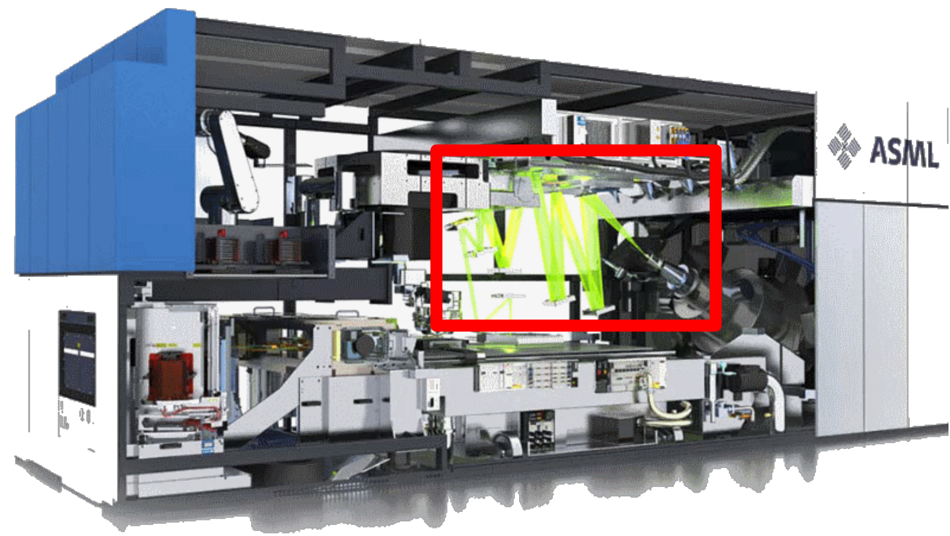
Lithography light sources resistant to Moore's Law



- Use of optical techniques to push resolution lower with same wavelength
- Over two decades wavelength decreased by only factor of 2
- EUVL will decrease wavelength by 10x: from 193 nm to 13.5 nm

NIST National Institute of Standards and Technology

Extreme Ultraviolet Lithography is here!



ASML NXE 3100

~10 Watts in [13.23-13.77] nm

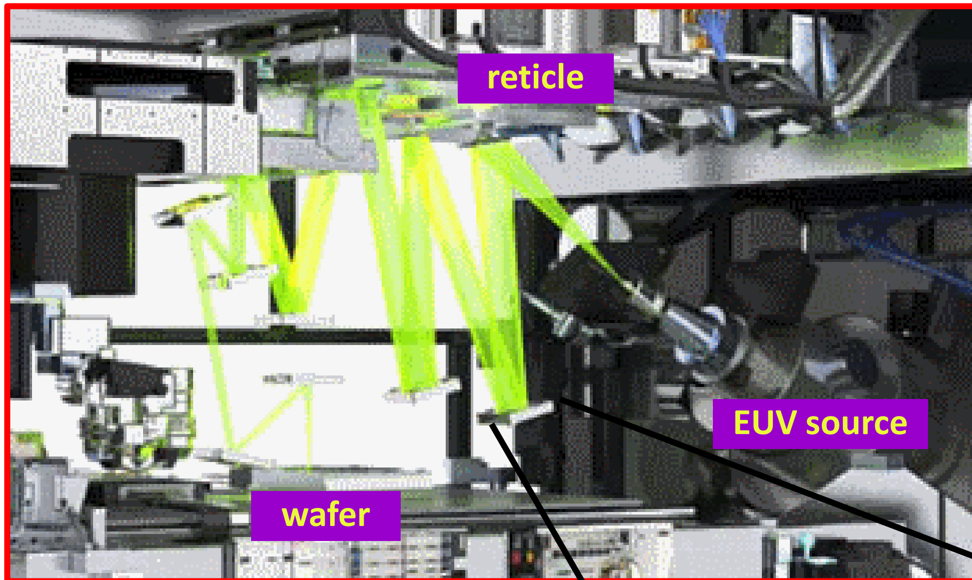
- Pre-production tool
- Multiple units shipped & operational
- Wafers printed per hour:
  5 demonstrated, 60 projected
- Designed for 27 nm, extendable to 18 nm

ASML NXE 3300B

150-250 Watts in [13.23-13.77] nm

- Production tool
- Multiple orders, shipment mid 2012
- Up to 125 wafers per hour
- Designed for 22 nm, extendable to 16 nm

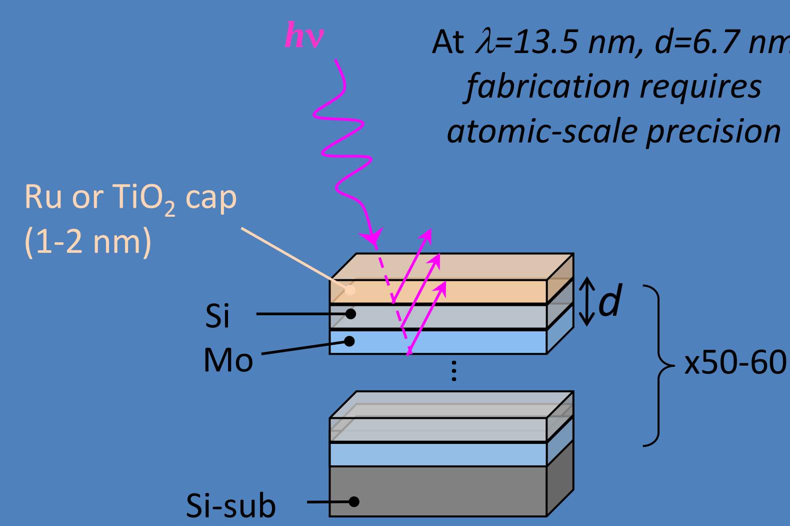
EUVL requires *reflective* optics



Reflectivity ~ 69% at
λ=13.5 nm   2% (92 eV)

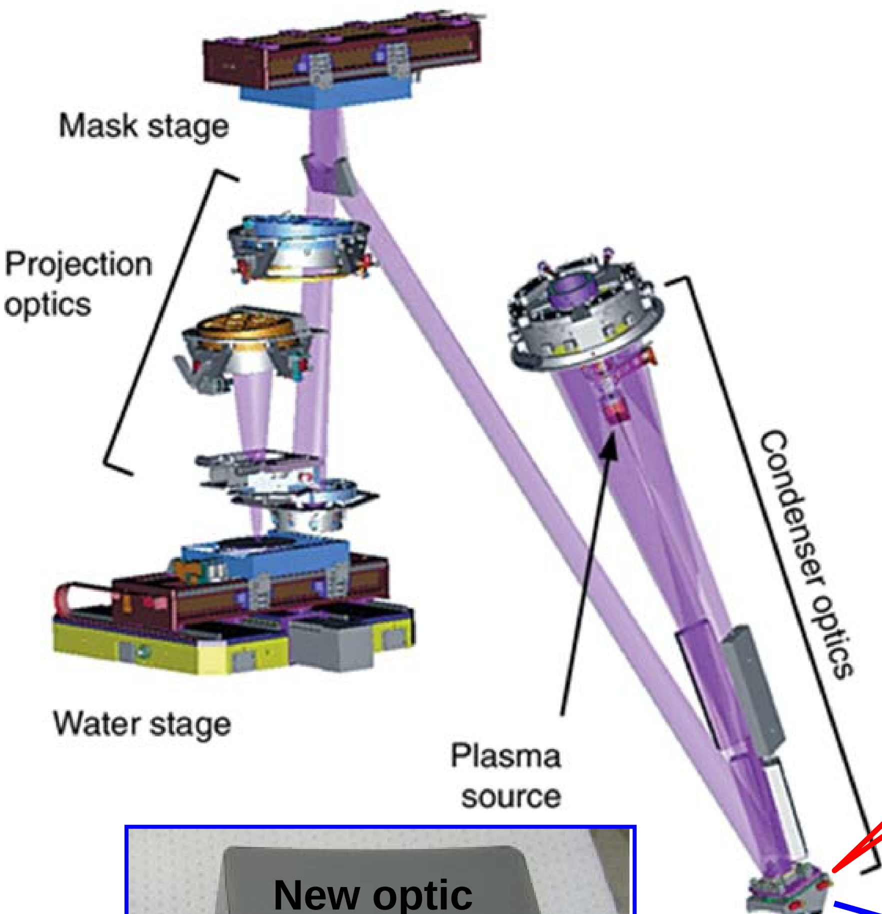
Multilayer mirror (MLM)

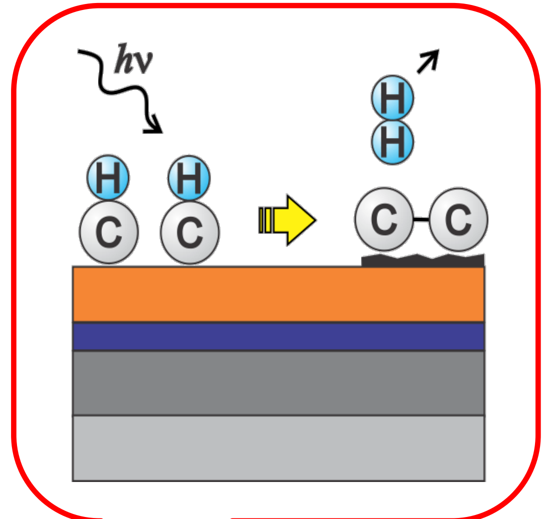
Reflection by Bragg interference: **λ = 2 d sinθ**

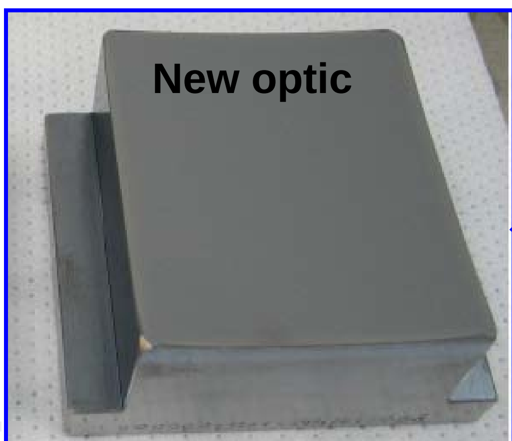


- Maximum net throughput for 6 mirrors: $T_0=(R_0)^6$ ~11%
- 6% total transmission loss per 1% reflectivity loss of each optic

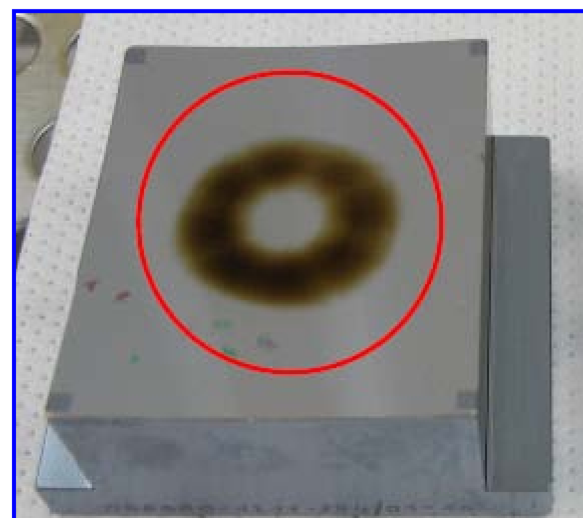
Contamination on first proto-type EUVL tool





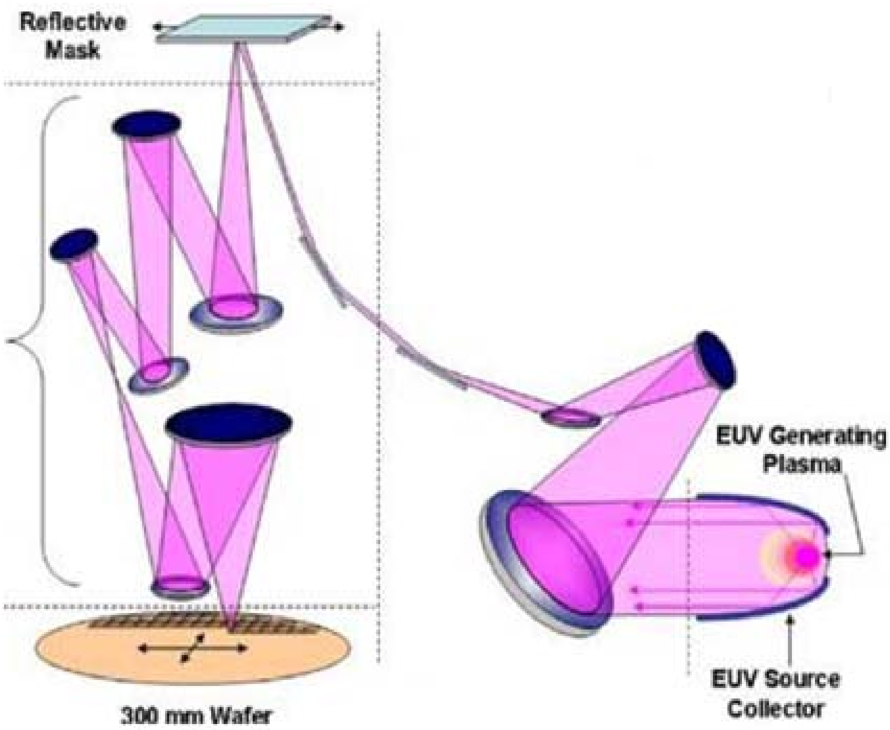


After *limited* use (~2 wafers)



Images courtesy of SEMATECH

Metrology of optics lifetime

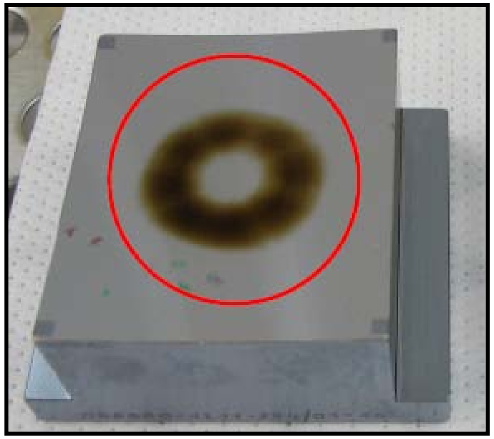


How does contamination vary with

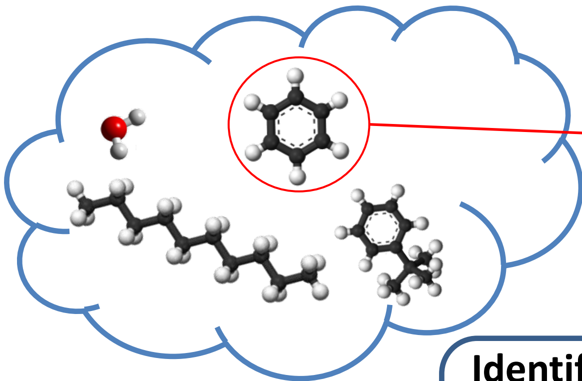
- Contaminant species
- Partial pressure of contaminant
- Partial pressure of water vapor
- EUV intensity
- Duty cycle of pulsed EUV sources
- Wavelength
- Time (EUV dose)

How is contamination measured

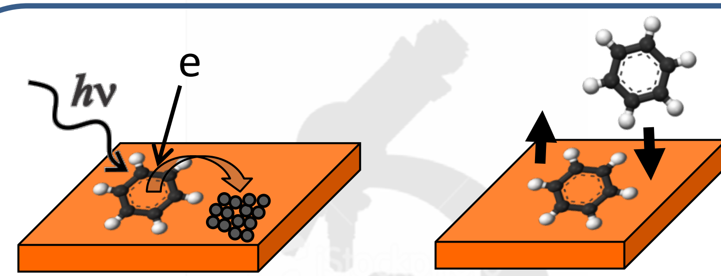
- Reflectometry
- X-ray photoelectron spectroscopy (XPS)
- Spectroscopic ellipsometry (SE)
- Other techniques: NEXAFS, RBS, TEM…



Contamination Studies at NIST and Rutgers Univ.



Identify potential contaminants:
chamber & resist out-gassing (RGA, GC-MS)

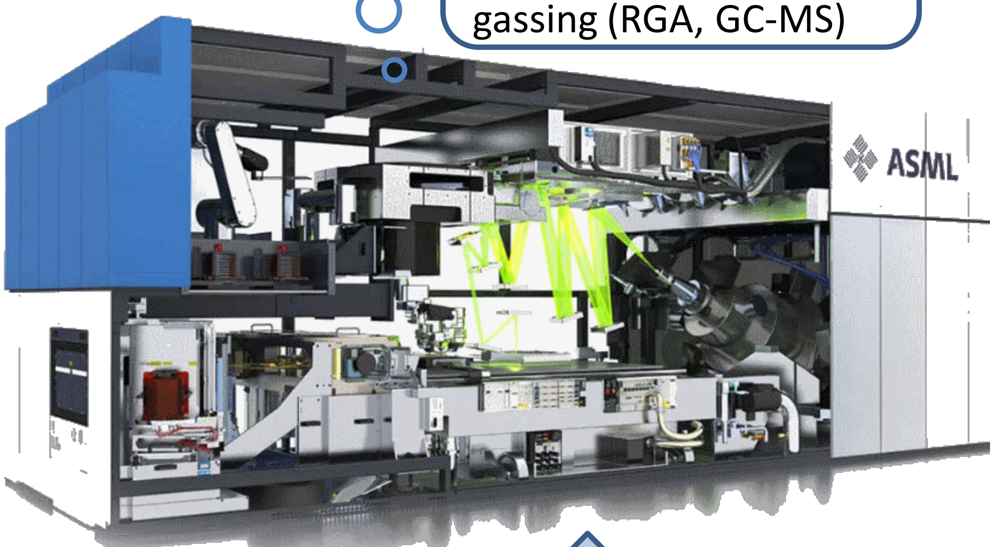


Contamination kinetics
- EUV photons (*NIST*)
- *e-beam (Rutgers)*
- XPS, SE, NEIS, LEIS

Adsorption/desorption
- *Rutgers/Tulane*
- NO irradiation
- TPD, LEIS, XPS

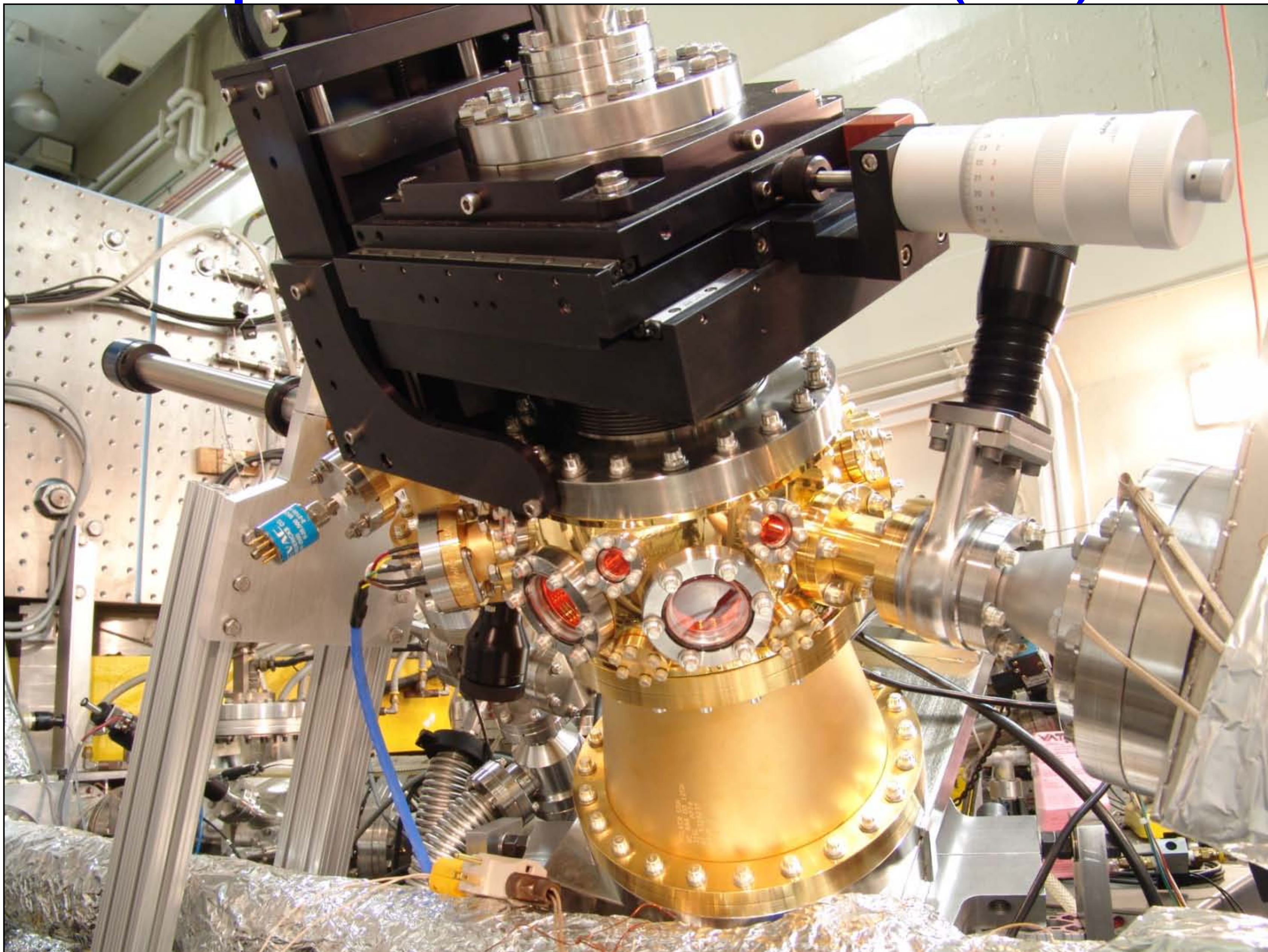
Contamination rates
Scaling laws
Mitigation techniques

Optics lifetime estimates/strategies



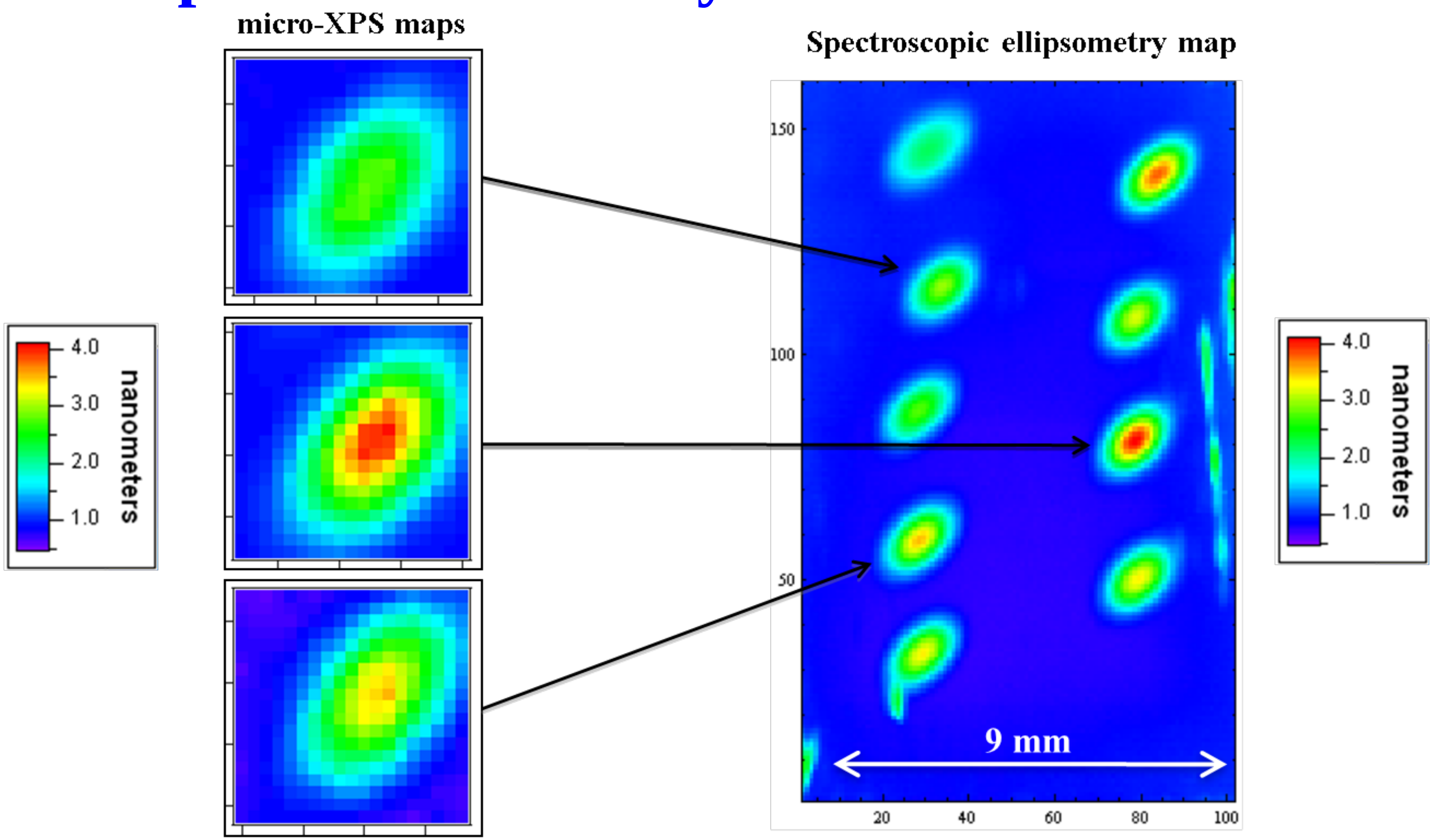
NIST
National Institute of Standards and Technology

Optics contamination beamline (BL8)



m^2

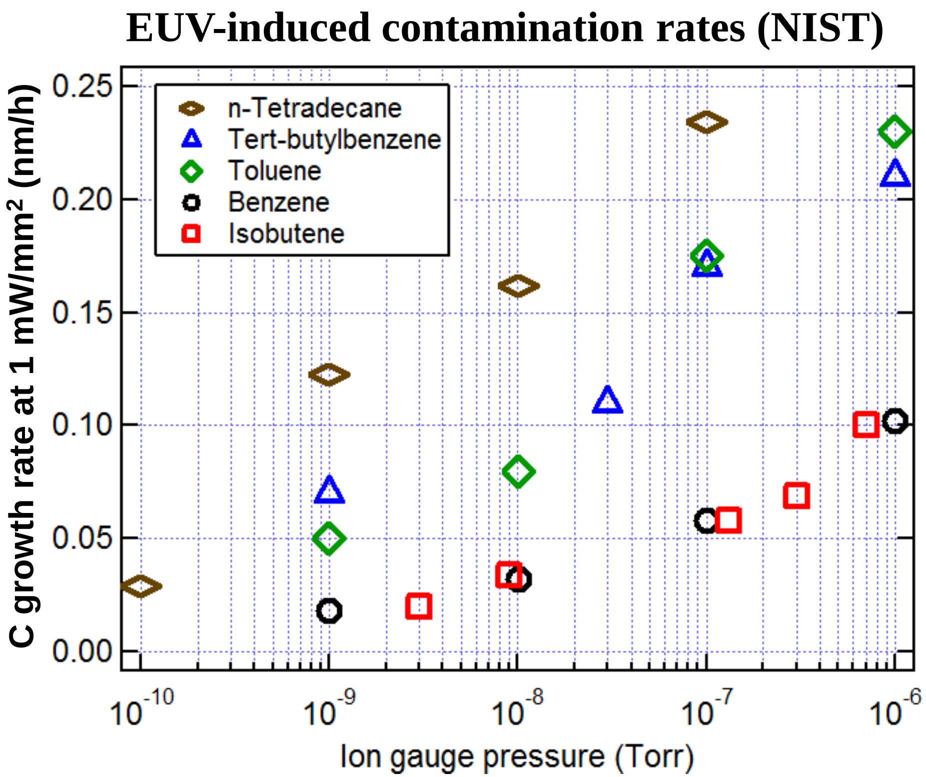
C deposits measured by *ex situ* XPS and SE



X-ray photoelectron spectroscopy (micro-XPS)
- Direct measure of composition
- Mapping slow (low sensitivity for sub nm)
- Absolute accuracy depends on assumed electron scattering length

Spectroscopic ellipsometry (SE)
- Few-Angstrom sensitivity
- Can map entire sample in <16 hrs
- Thickness accuracy determined by fit of optical constants to data.

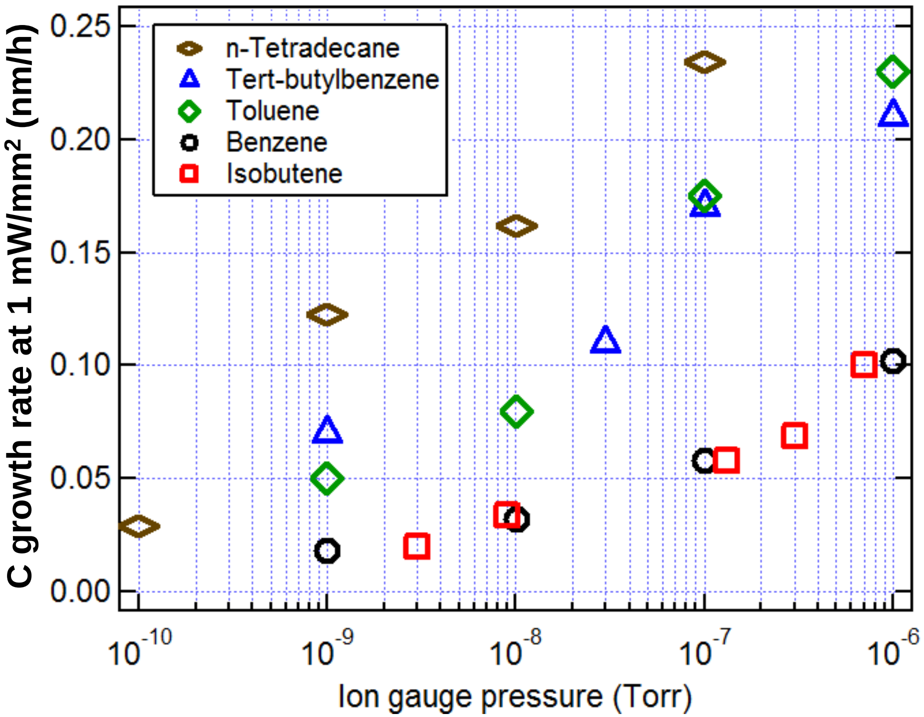
Contamination rates measured over large pressure range



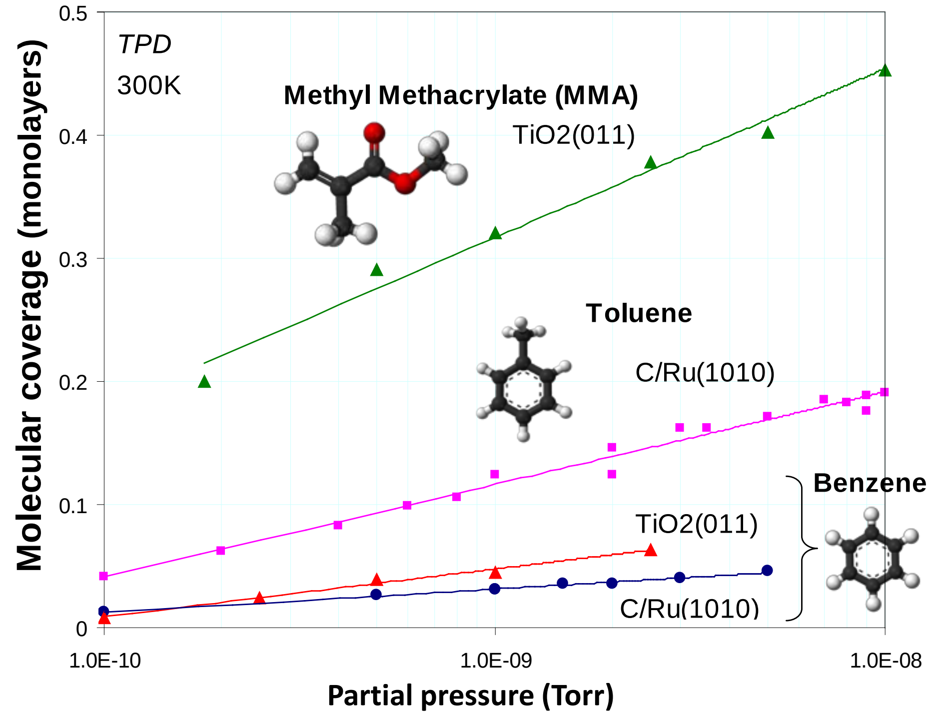
- Contamination rates vary with log of pressure below 10^{-5} Torr for every species tested.
- Linear pressure scaling reported elsewhere at much higher pressures.
- Essentially impossible to completely eliminate contamination by clean vacuum practices alone.

Pressure scaling of EUV contamination rates driven by fundamental surface physics

EUV-induced contamination rates (NIST)



Equilibrium coverage (Rutgers, *no EUV*)



- EUV contamination *and* equilibrium molecular coverage (non-irradiated) scale with log of pressure
- Rate of EUV-induced C deposition proportional to equilibrium coverage of adsorbed precursor molecules.

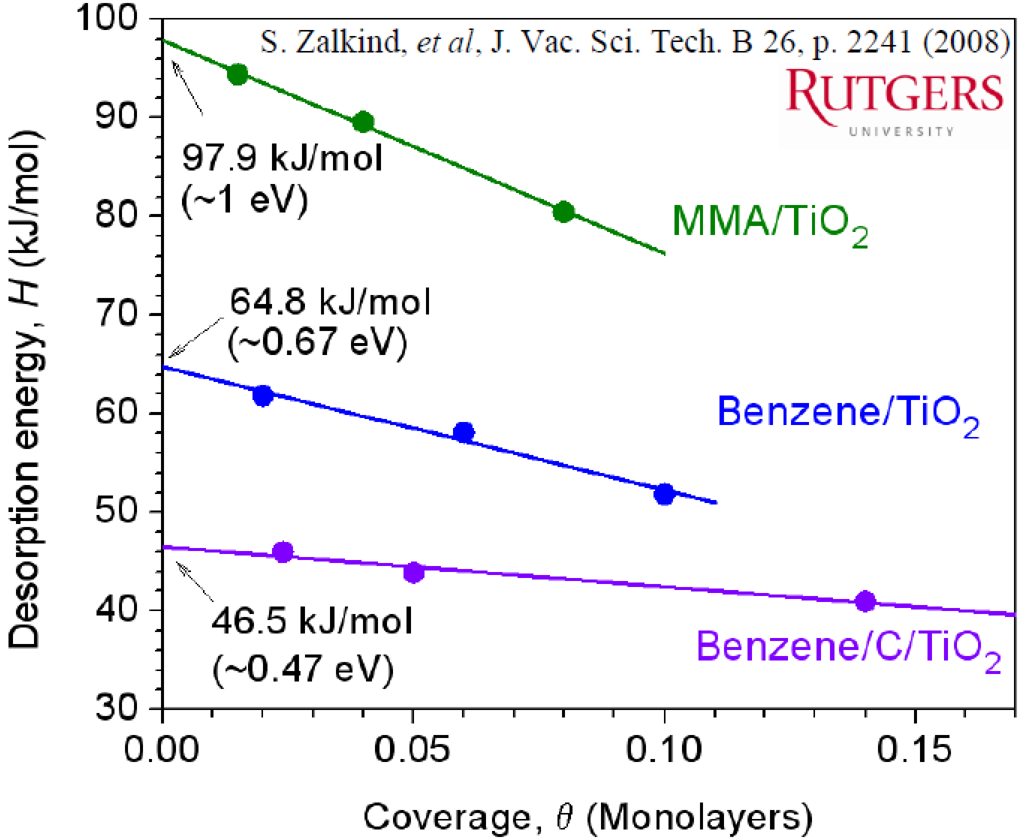
If observed decrease in instrument responsivity is due to contamination, would expect the rate to change VERY slowly with decay of outgassing products.

NIST
National Institute of Standards and Technology

Coverage-dependent desorption energy

Typical temperature of satellite instrument optics?

- Ideal Langmuir kinetics assumes fixed **desorption energy, *H*.**
- Rutgers measurements: *H* decreases linearly with **coverage, *θ***



- Desorption rate $= \nu_0(\theta) \cdot e^{\frac{-H(\theta)}{kT}}$

Temkin isotherms

- Molecular repulsion: $H(\theta)=H_0 - \alpha \cdot \theta$

$$\theta \propto \log\left(p/p_0\right)$$

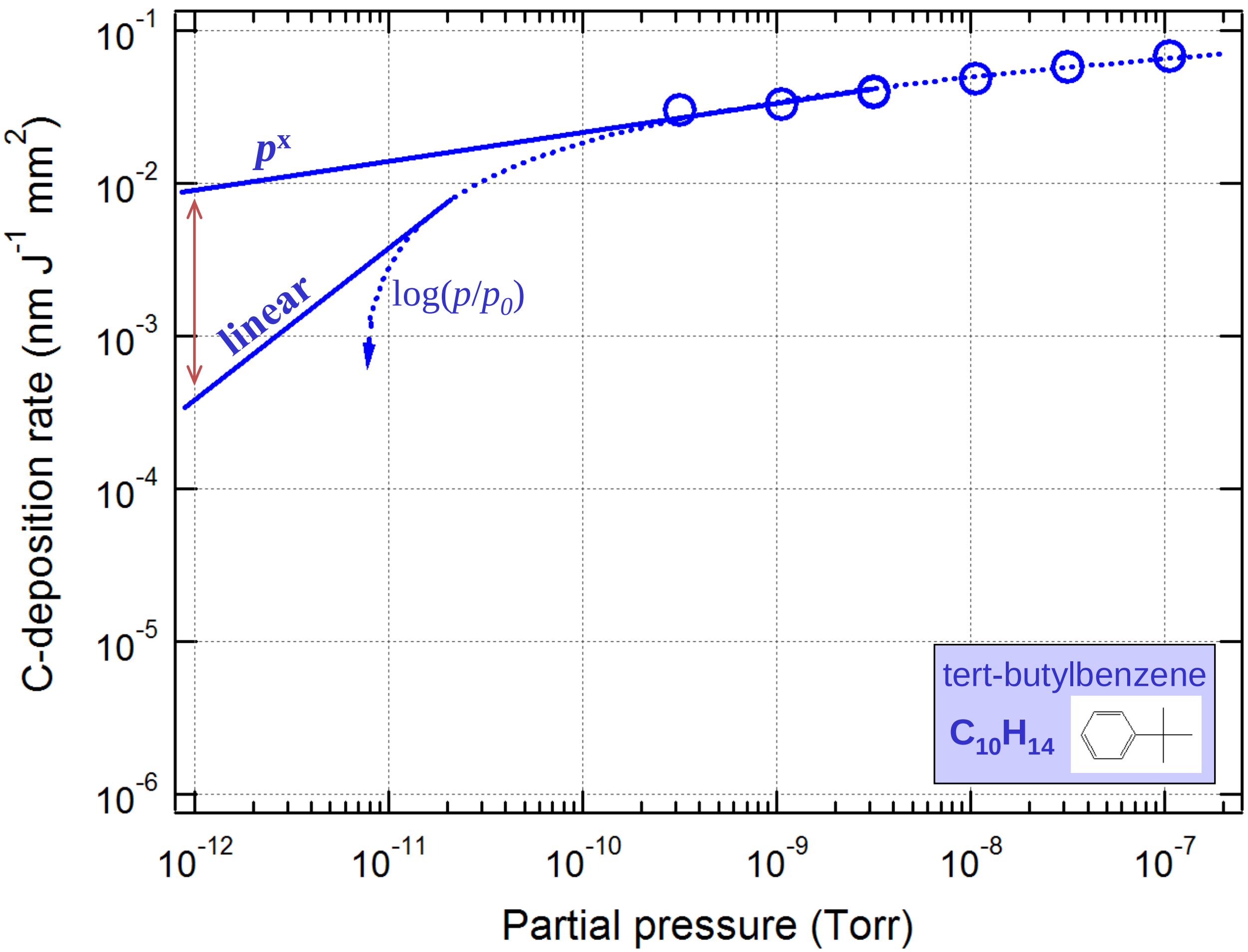
- Non-uniform surface: distribution of H

$$\theta = \log\left(\frac{1+a \cdot p}{1+b \cdot p}\right)$$

- As $p \to 0$ most models predict transition to linear scaling: $\theta \propto p$

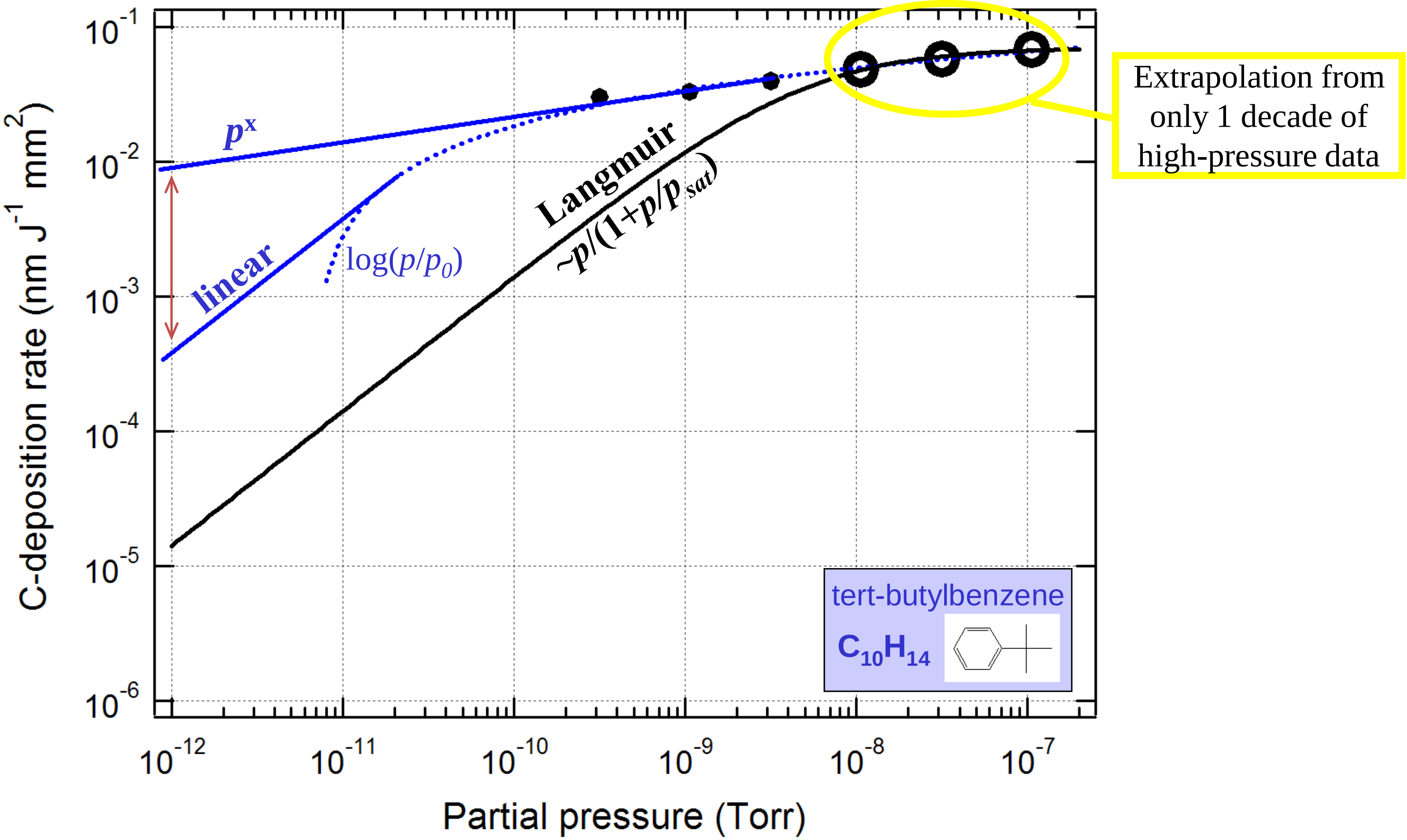
NIST National Institute of Standards and Technology

Extrapolation from accelerated testing to HVM tool conditions



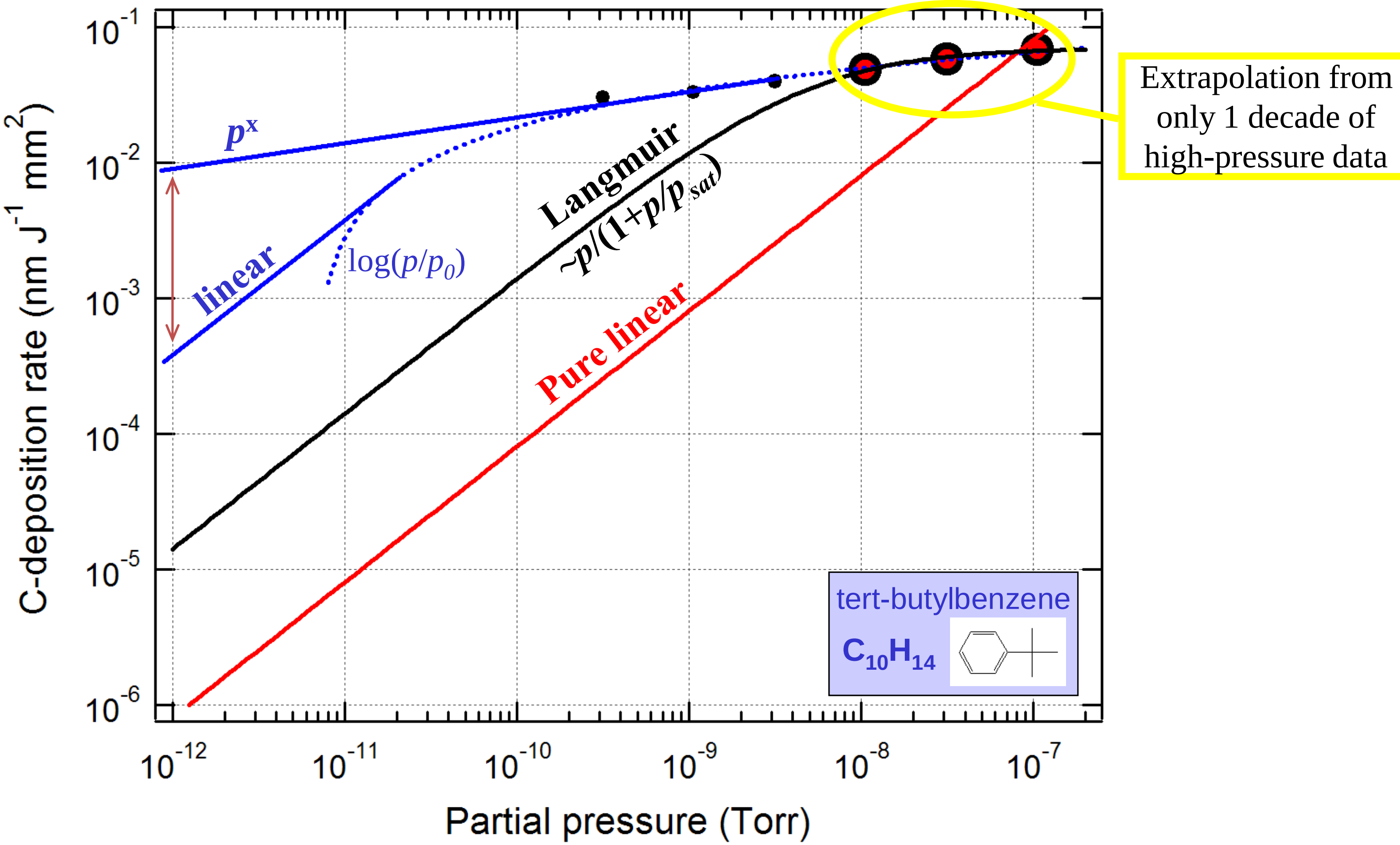
- Transition from $\log(p)$ not observed: estimate extrapolation limits

Extrapolation from accelerated testing to HVM tool conditions



- Transition from log(p) not observed: estimate extrapolation limits

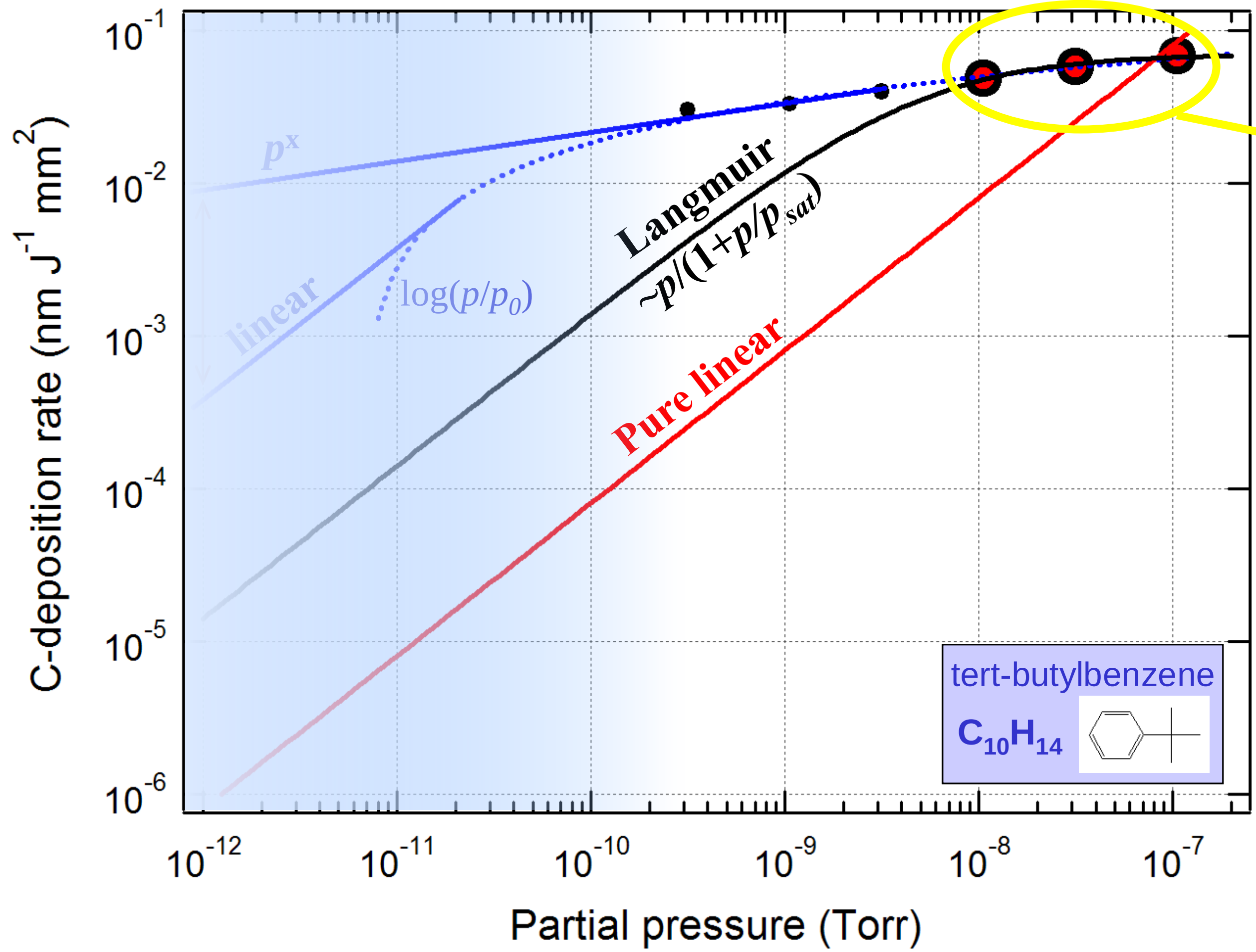
Extrapolation to lower pressures: potential errors



- Transition from log(p) not observed: estimate extrapolation limits
- Linear extrapolation of a few high-pressure measurements will *underestimate* rates at lower pressures by *multiple orders of magnitude*.

NIST
National Institute of Standards and Technology

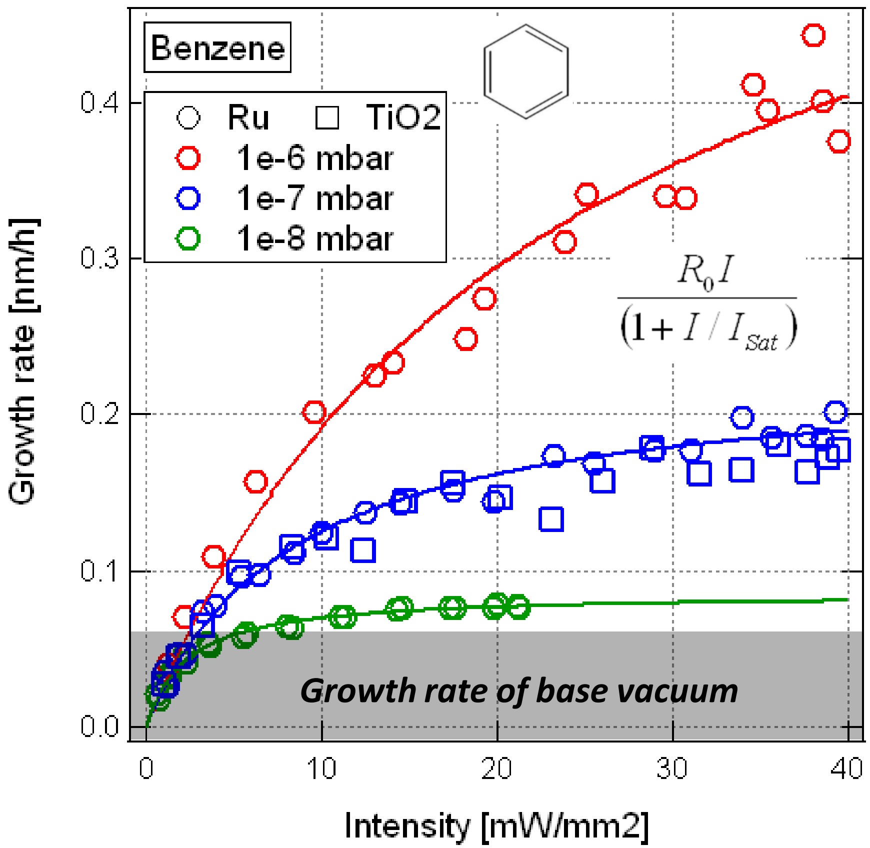
Extrapolation to lower pressures: potential errors



Extrapolation from only 1 decade of high-pressure data

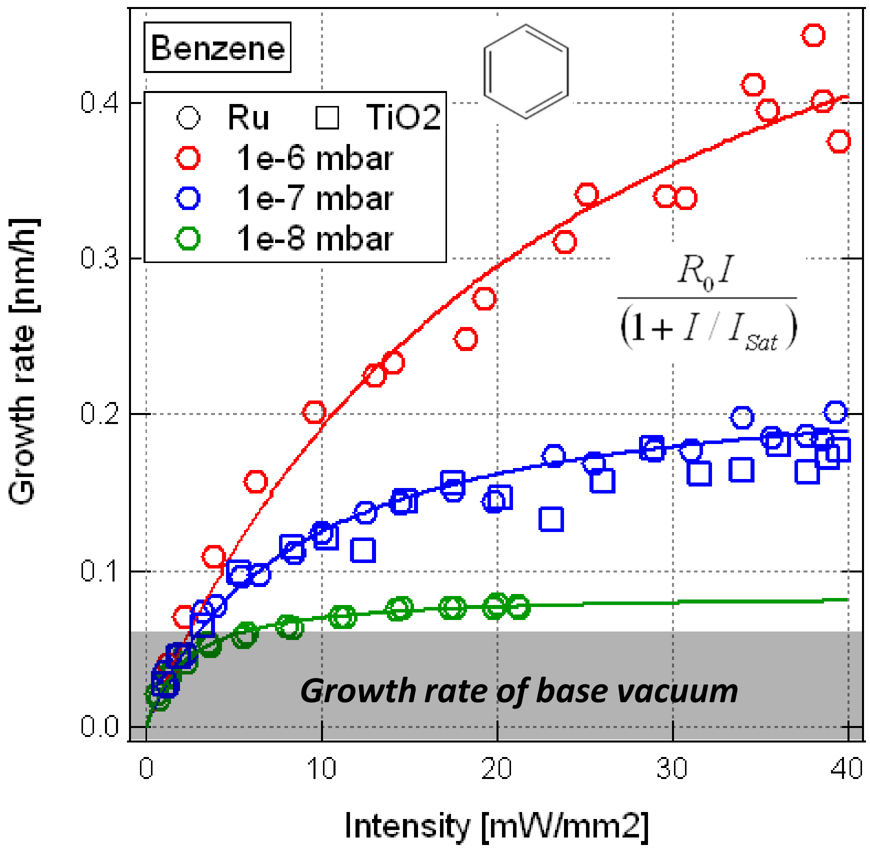
- Mitigation/cleaning by EUV + **ambient water vapor** can play important role at low partial pressures of contaminant species.
- Scaling at lowest pressures determined by intensity…

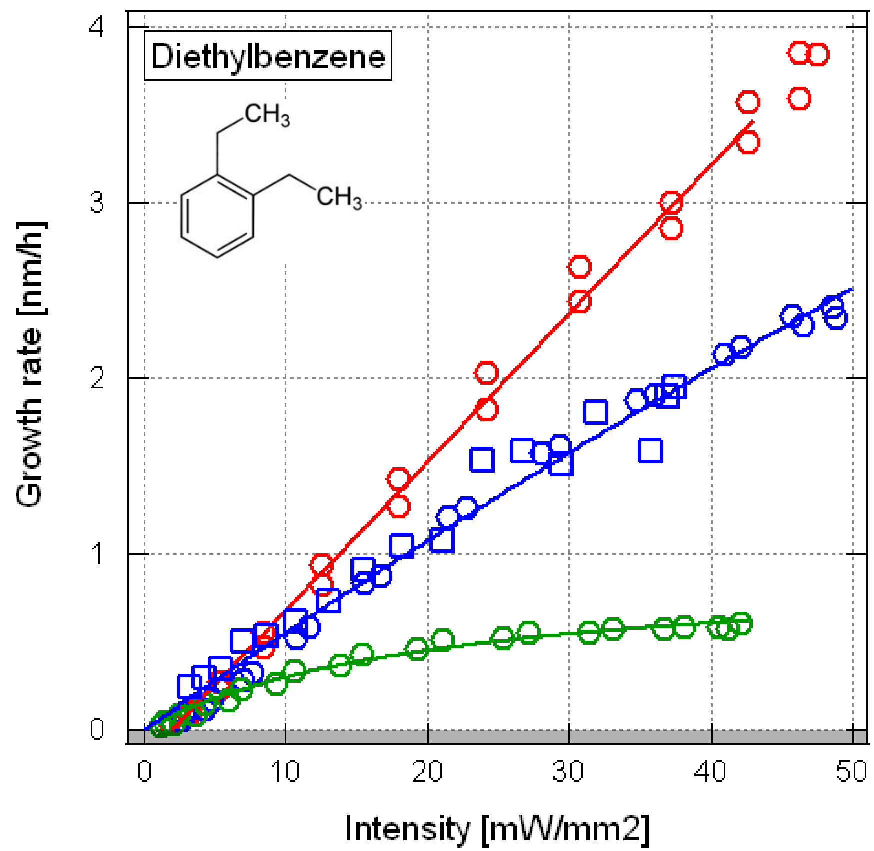
Intensity scaling: saturation & mass-limited growth



- C growth rate is *mass limited* for $I > I_{sat}$: every adsorbed molecule photo-reacts.
- I_{sat} increases with pressure and varies with species.

Intensity scaling: saturation & mass-limited growth



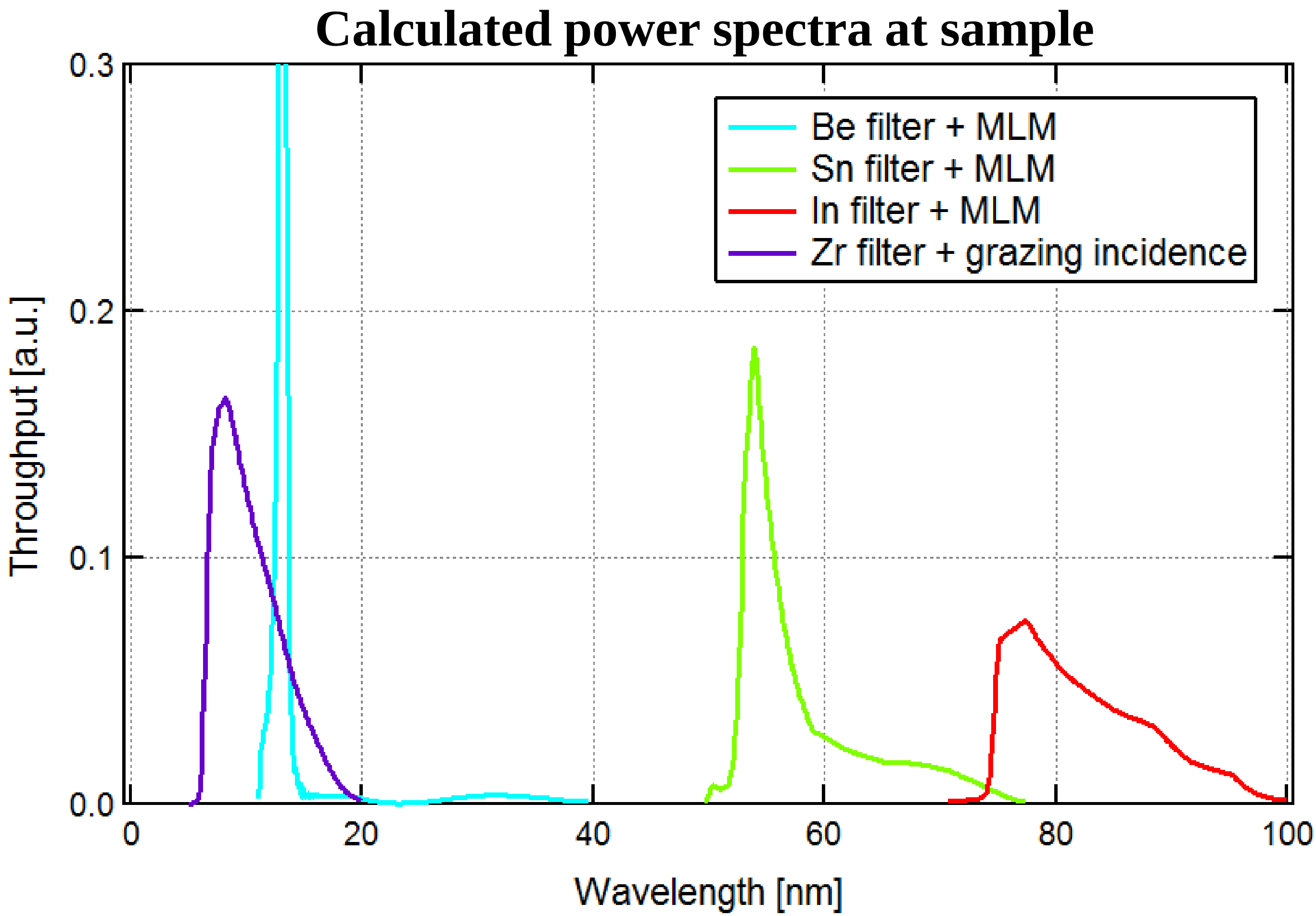


- C growth rate is *mass limited* for $I > I_{sat}$: every adsorbed molecule photo-reacts.
- I_{sat} increases with pressure and varies with species.
- *Pressure* scaling of rates changes from logarithmic to linear for $I > I_{sat}$.
- Contamination rate for $I > I_{sat}$ is maximum possible rate for given partial pressure.

For much lower solar irradiances, expect contamination to stay in linear regime.

National Institute of Standards and Technology

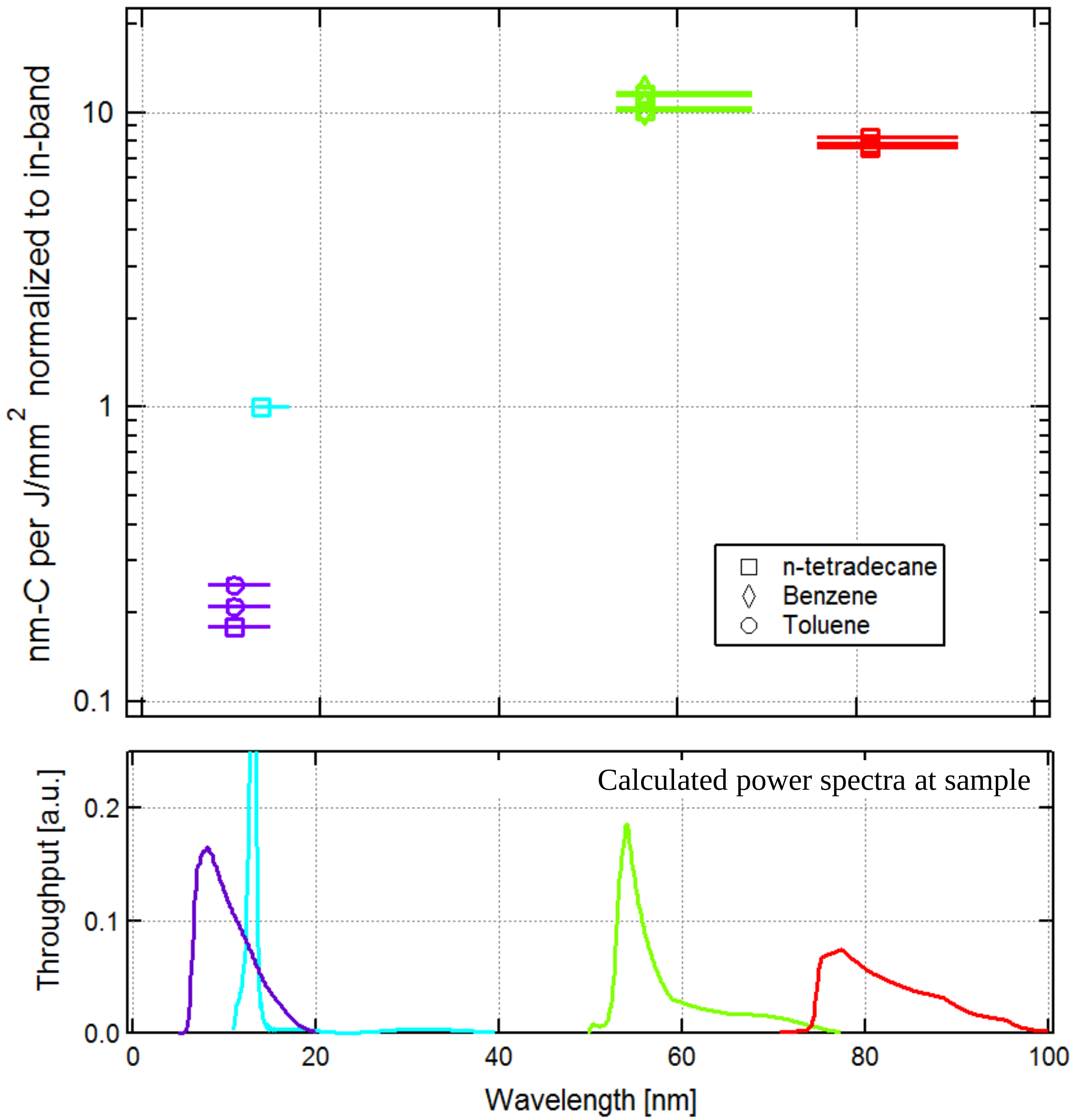
Study contamination at different wavelengths



- Grazing-incidence mirror & Zr filter used on resist-outgas beamline for higher intensity.
- Contamination rates were lower than expected with broadband light below 13.5 nm.
- Compare contamination rates over range of wavelength bands using normal-incidence multilayer mirror with **Be**, **Sn** or **In** filters.

NIST National Institute of Standards and Technology

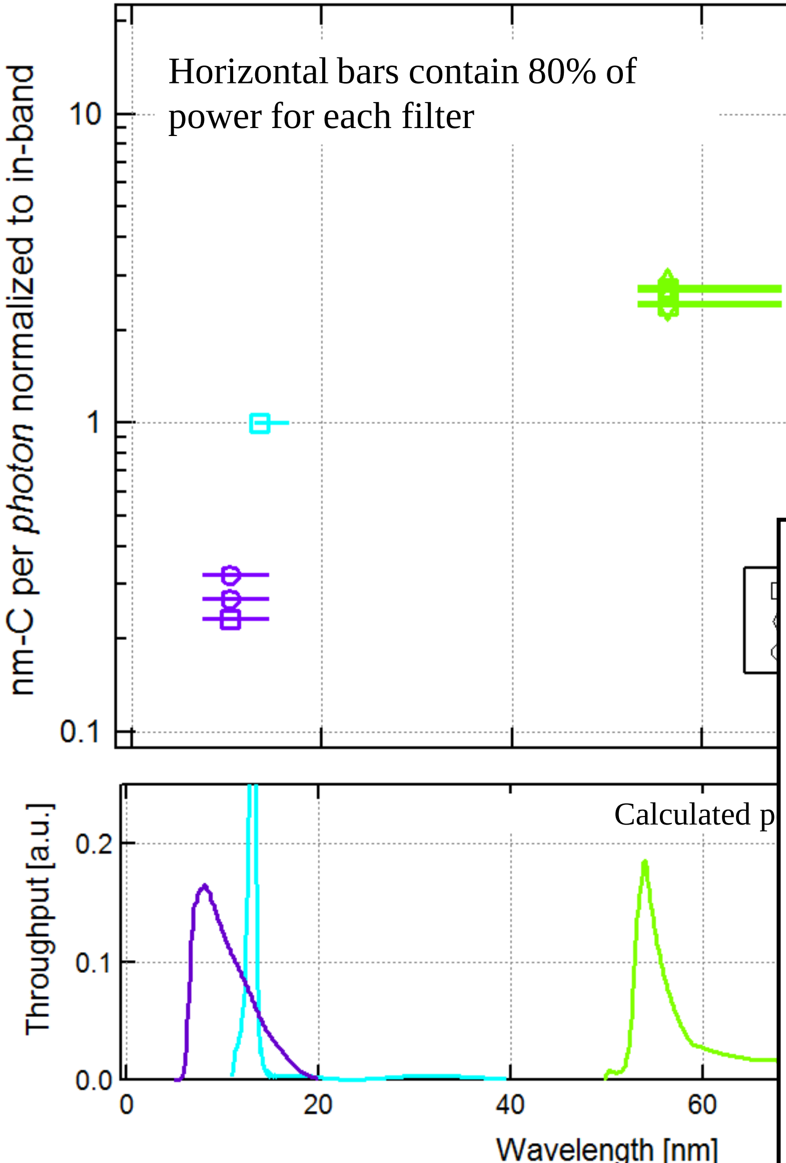
Wavelength scaling of contamination rates



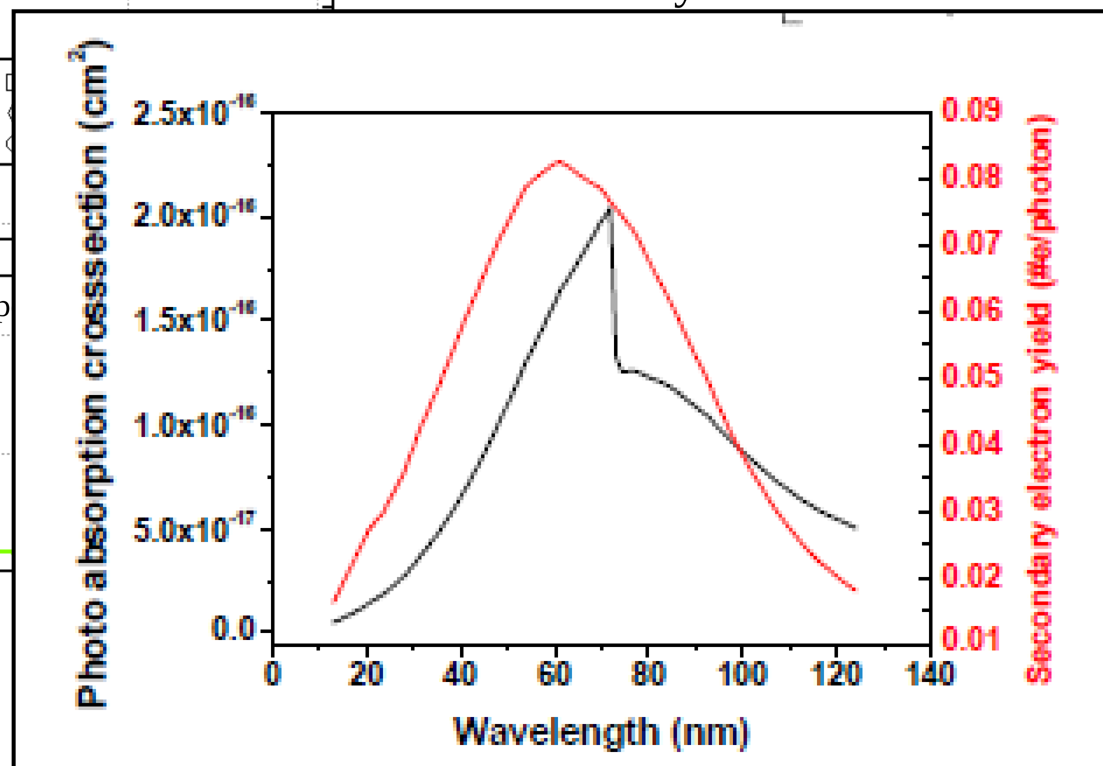
- Compare ratio of rates at different wavelengths to in-band rates (**MLM + Be filter**).
- Horizontal bars contain 80% of power for each filter
- Rates for different species over wide range of pressures display same dramatic increase between ~10 nm and ~60 nm. (*note log scale*).
- Consistent with previous measurements (Denbeaux, SPIE 2010) and calculations (Jindal, SPIE 2009.)

NIST National Institute of Standards and Technology

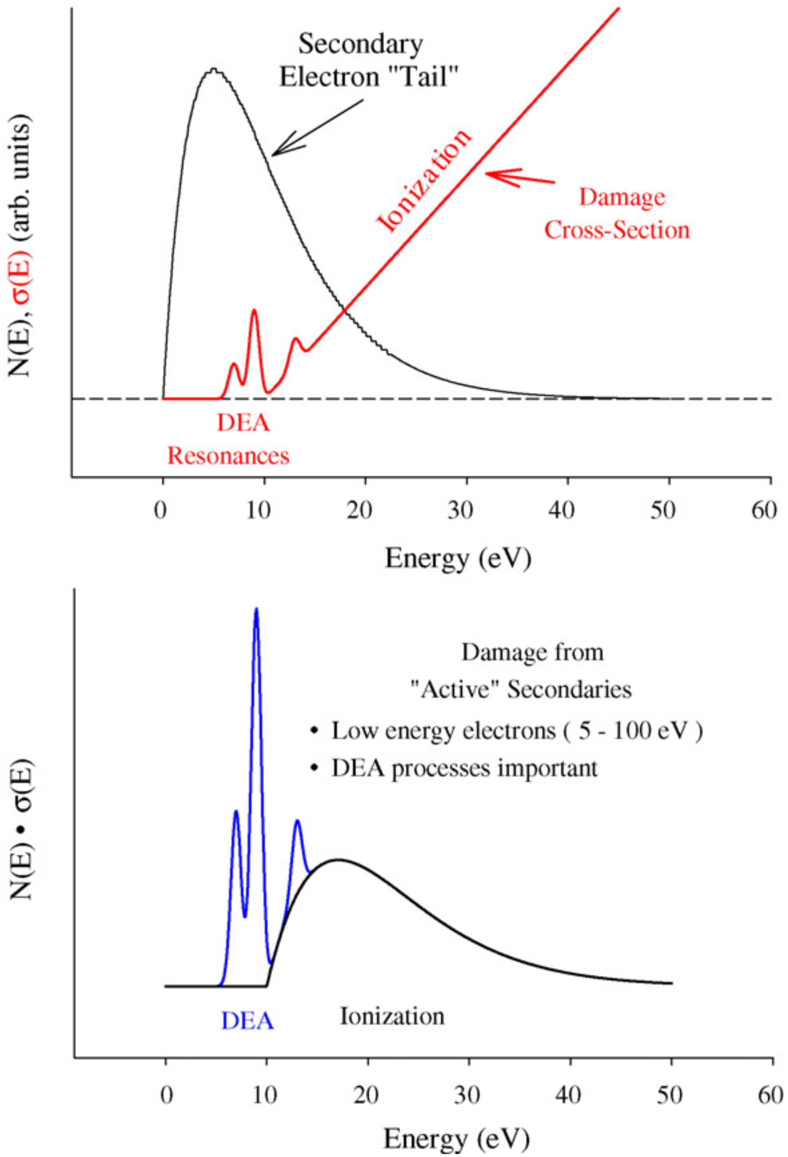
Wavelength scaling of C deposition *per photon*



- Contamination per photon also shows significant increase.
- Higher rates *not* just due to more photons.
- Measurements with (110-200) nm filter underway.



Suspected mechanism of contamination



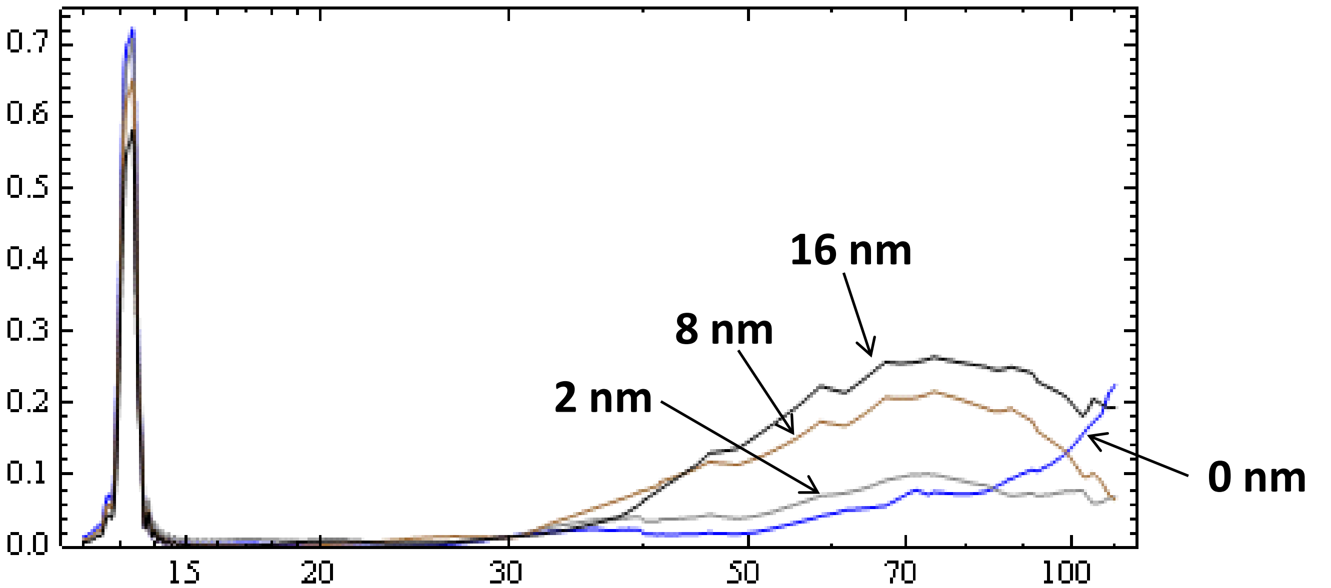
- Contamination thought to be driven by secondary electrons, not primary photons
- Many low energy (<10 eV) electrons available
- Dissociative electron attachment (DEA) cross sections can be significant at low energies.

Fig. 10. Schematic curves illustrating the importance of low energy secondary electrons (SE) on DIET processes. $N(E)$ is a typical SE energy distribution, and $\sigma(E)$ shows damage cross sections vs. electron energy. The DEA resonances dominate at low energies, and dissociative ionization occurs at higher electron energies. The lower panel shows that the convolution of SE yield and damage cross section emphasizes the role of dissociative electron attachment (DEA) processes, and illustrates the importance of low energy SEs. From Orlando and Meisel [74].

T.E. Madey et al. / Applied Surface Science 253 (2006) 1691–1708

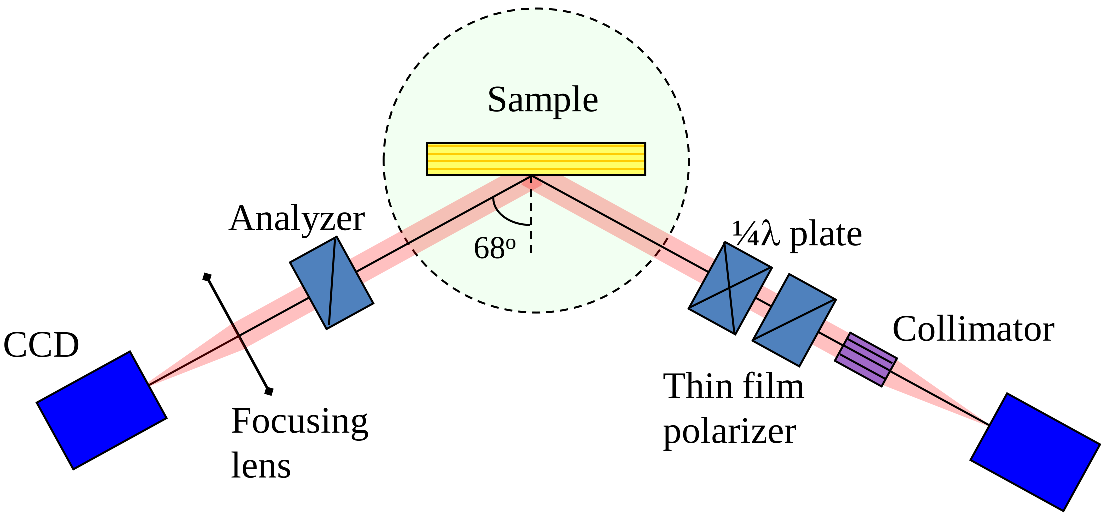
“Degradation” from C deposition can be non-monotonic

Reflectivity of Ru-capped MLM with varying thicknesses of C



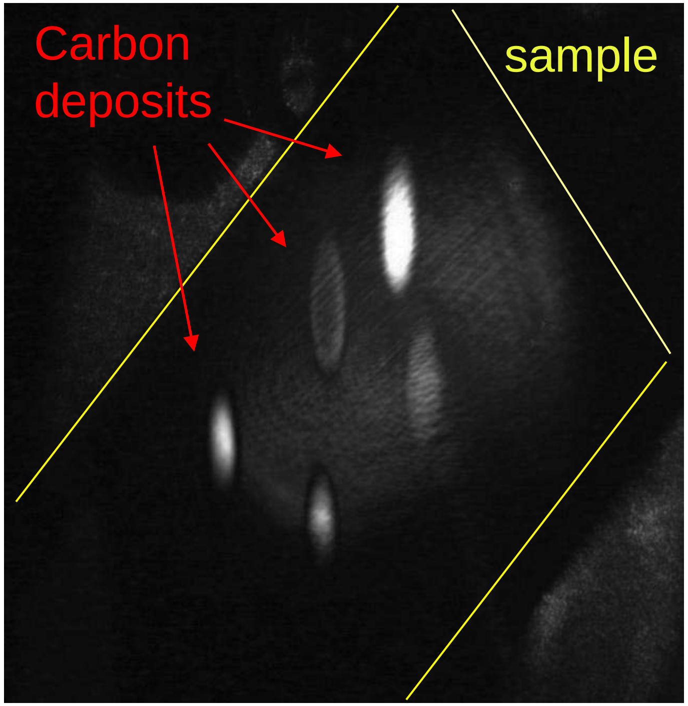
- Reflectivity of C is not negligible in 40-100 nm band
- Could enhance throughput of reflective components
- Would add to loss for transmissive components

Null-field Ellipsometric Imaging System (NEIS)



Jin et al, Rev. Sci. Instrum 67(8) (1996) 2930
Garg et al Proc. SPIE, 7636-131 (2010)

In situ image of C thickness (BL8)

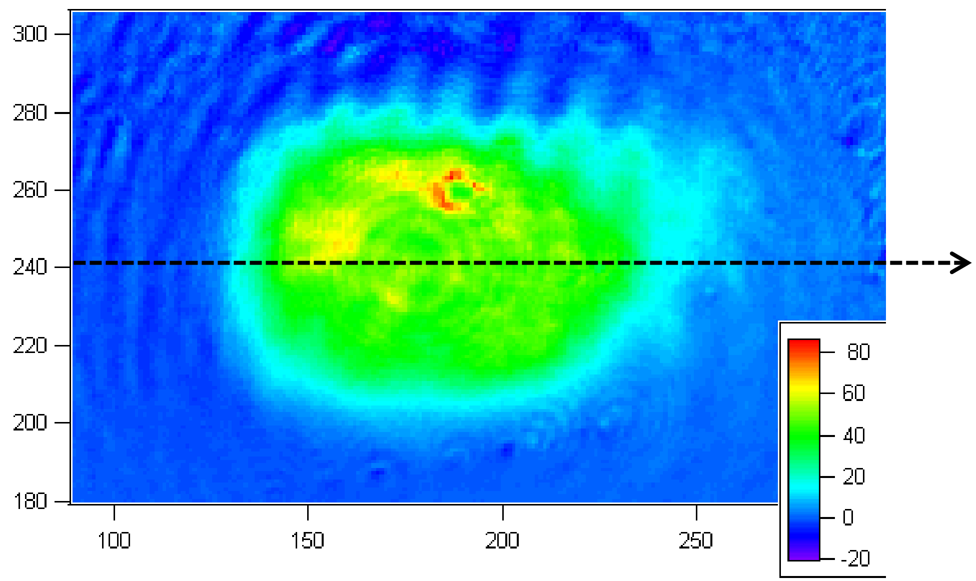


- Set polarization elements to block light to CCD for native surface: "null condition"
- Any change in surface alters polarization and passes light to CCD
- For thickness, $T < 10$ nm, CCD intensity proportional to T^2
- Sub-nanometer thickness sensitivity; ~100 μm lateral resolution.

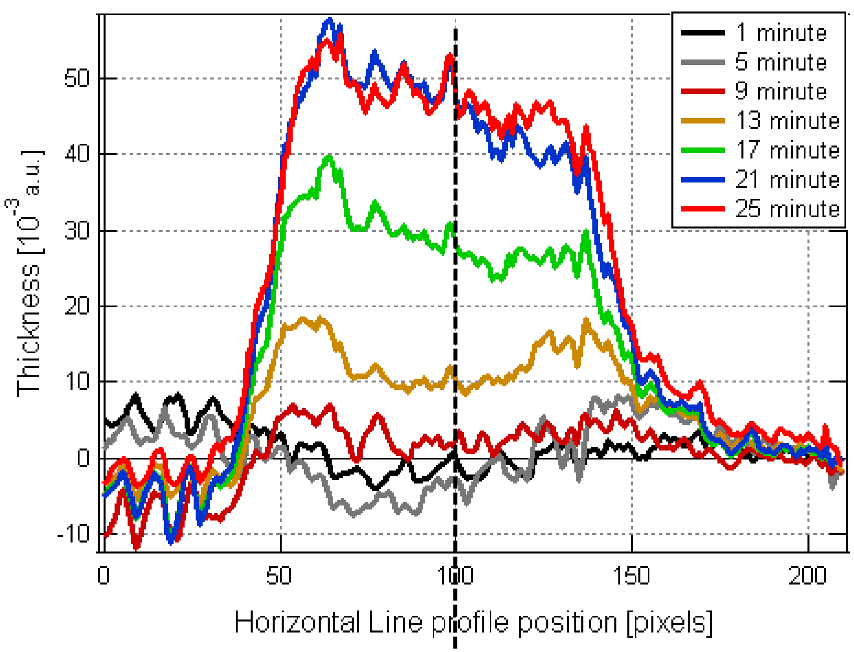
NIST National Institute of Standards and Technology

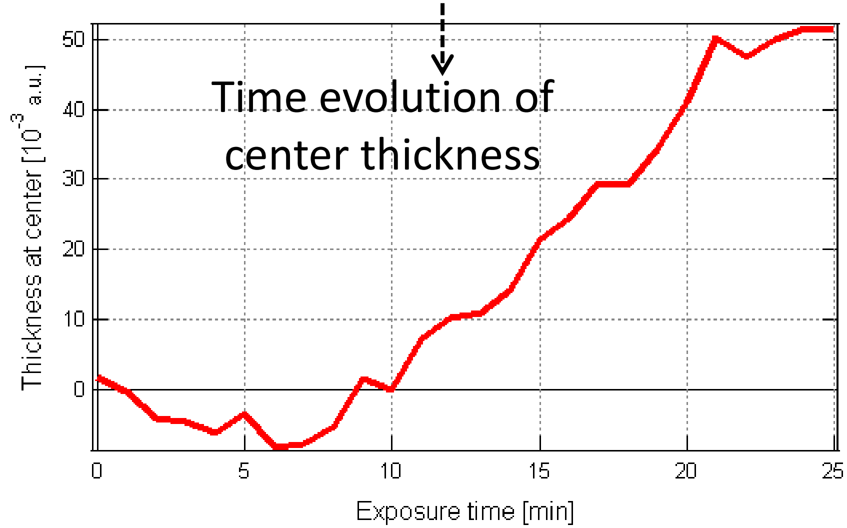
Evolution of exposure

Final NEIS image



Time evolution of line profile





- Significant contamination does not start until ~8 minutes into exposure
- Initial dip possibly photon-stimulated desorption (or compaction) of contaminants from air (hydrocarbons, water) or modification of native oxide.
- Then growth rate appears constant
- Mostly flat-topped throughout growth.

Thank you!

Ongoing work

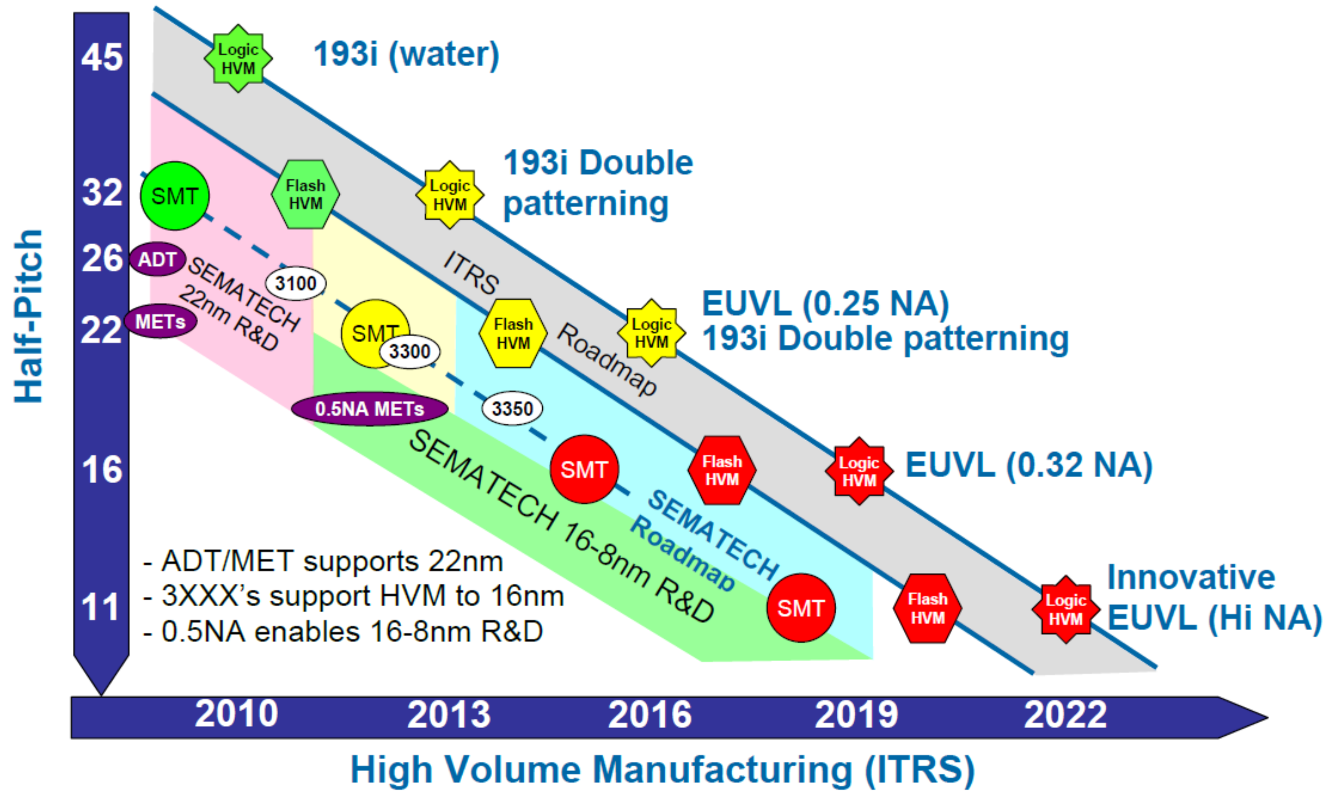
- Resist-outgas testing and qualification
- Effect of EUV intensity/dose on cleanability of C
- Correlation of metrologies: ellipsometry, XPS, reflectometry
- Cleaning with H-atom hot-filament and plasma, as well as EUV + H_2O_2, NO
- Non-C contamination: S, F, Cl, etc.

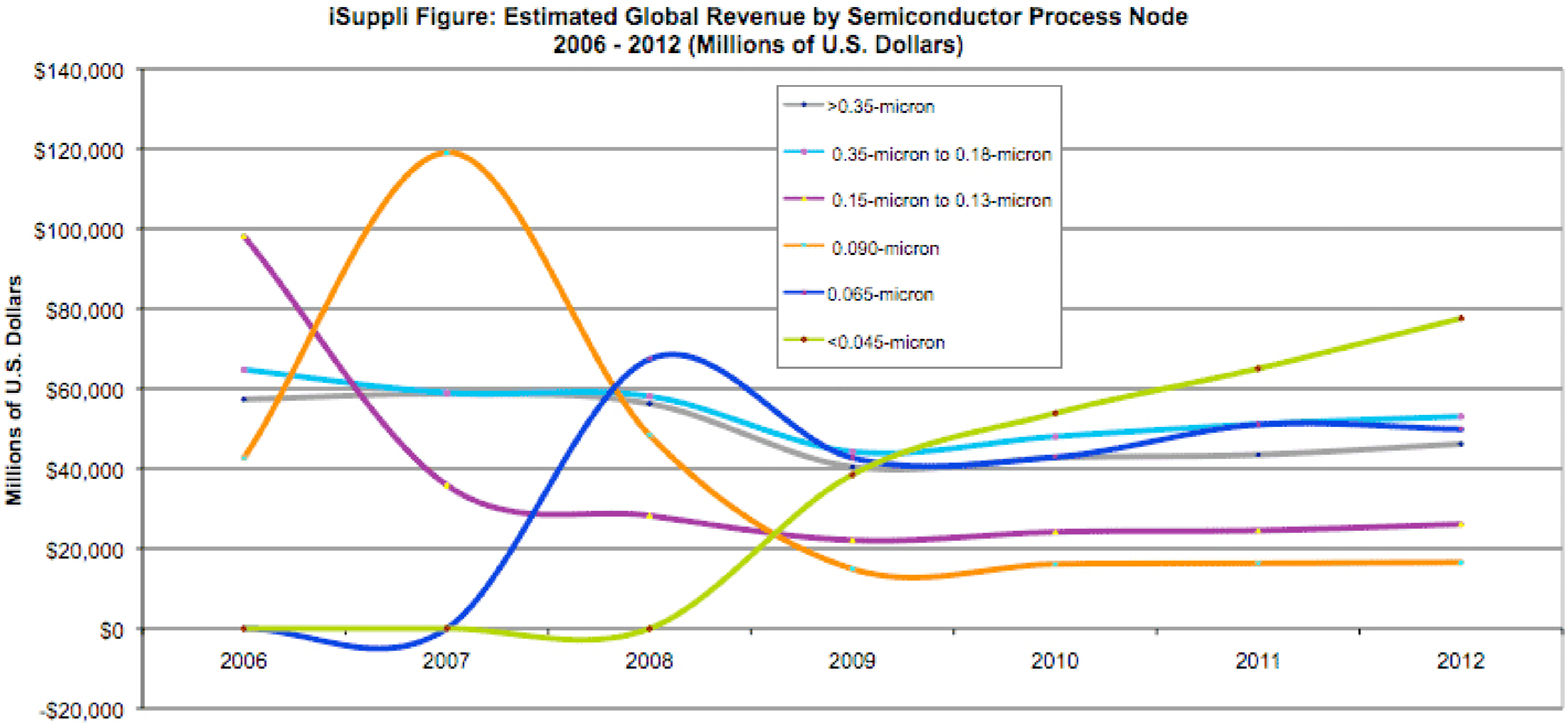
Supplemental Slides

Summary

- Pressure scaling of contamination rates is highly sub-linear (logarithmic)
- Intensity dependence saturates at species and pressure dependent I_{sat}
- Estimating contamination risks at tool conditions requires measurements over range of pressure and intensity.
- Out of band light may pose greater contamination threat than in-band for some optics.
- NXE3100/3200B resist qualification up and running at NIST.

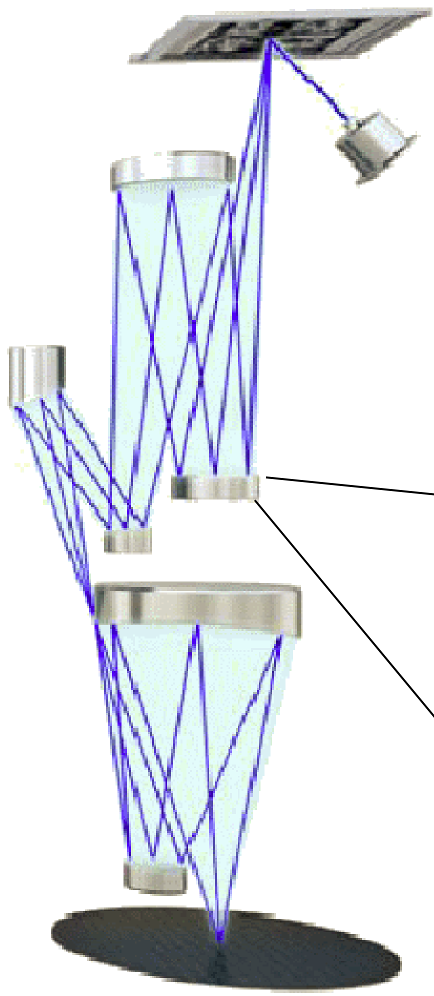
Lithography roadmap

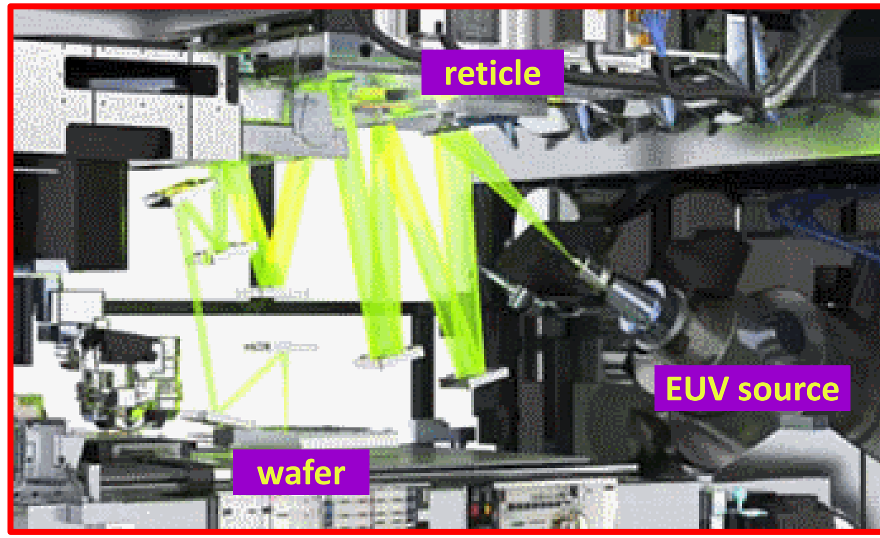




Source: iSuppli Corp. June 2009

EUVL requires *reflective* optics



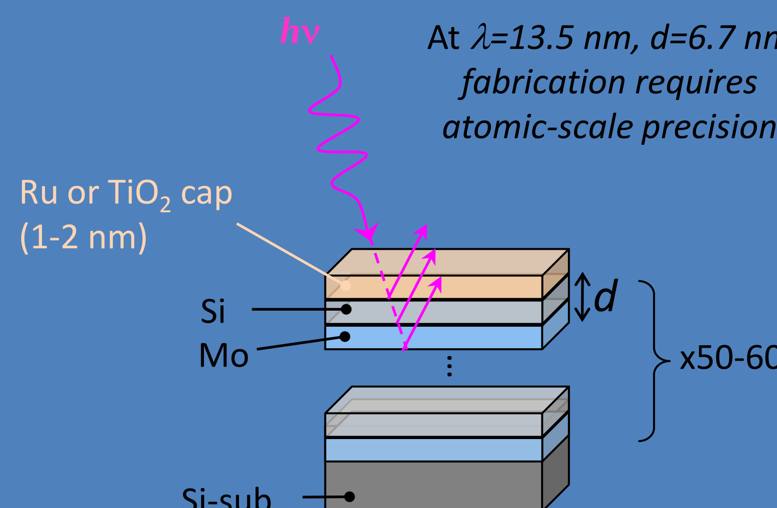


λ=13.5 nm (92 eV)
FWHM ~0.5-0.6 nm
R_0 ~ 69% (each mirror)

Multilayer mirror (MLM)

Reflection by Bragg interference: **λ = 2 d sinθ**

At λ=13.5 nm, d=6.7 nm fabrication requires atomic-scale precision

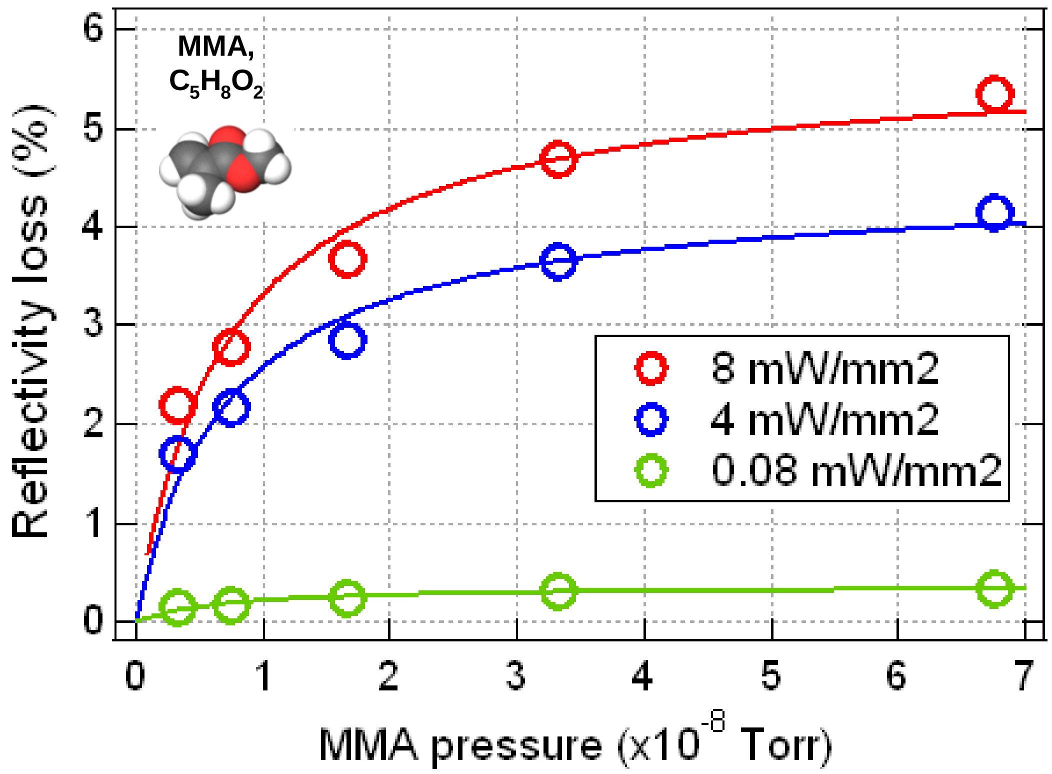


Max net transmission: $T_0=(R_0)^6$ ~11%
6% relative transmission loss
per 1% relative reflectivity loss

33

National Institute of Standards and Technology

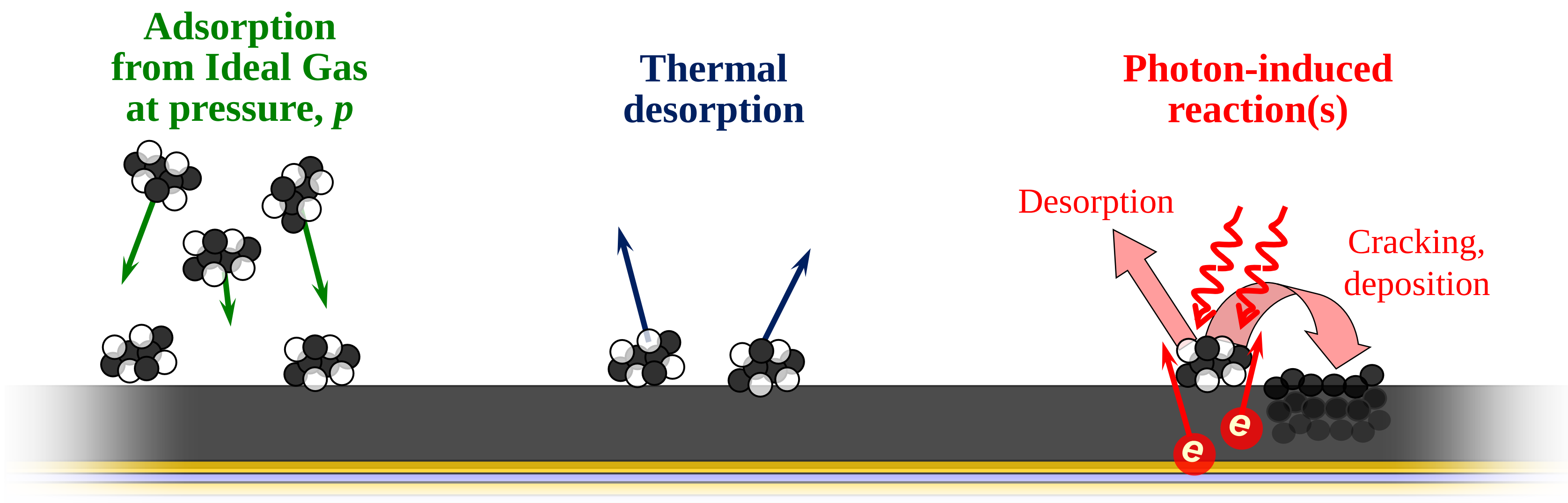
Initial EUV optics contamination studies (2007)



- Reflectivity loss of MLM sample after 13 h EUV exposure in methyl methacrylate (MMA) vapor.

NIST
National Institute of Standards and Technology

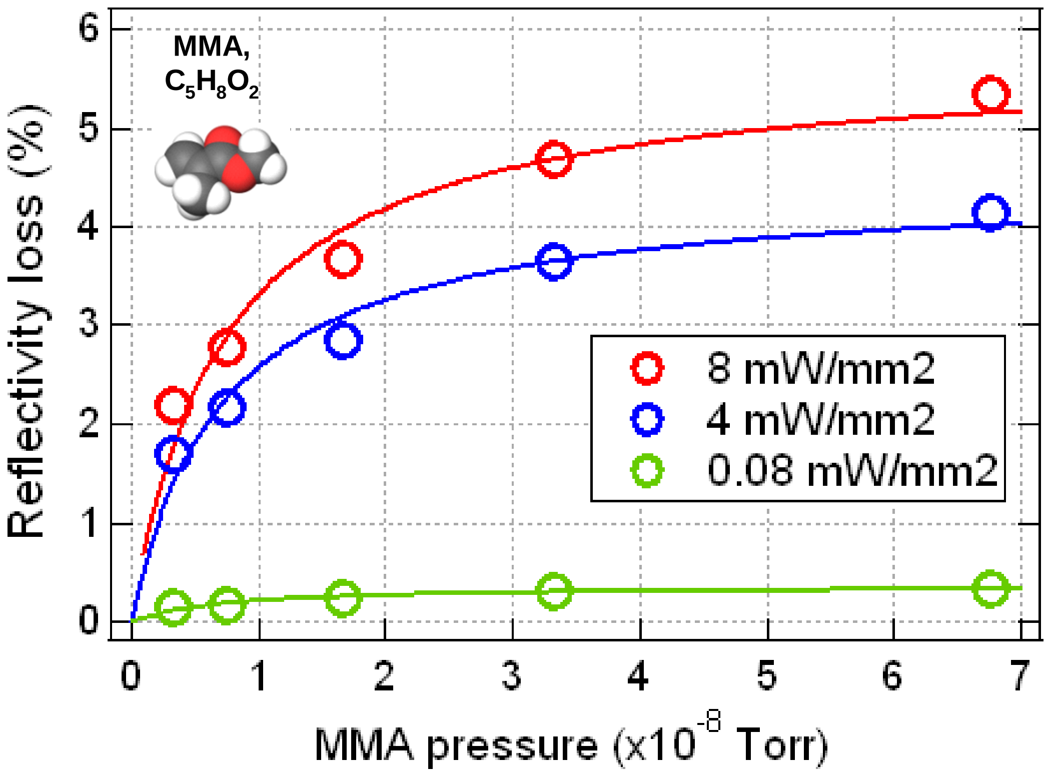
Pressure scaling predicted by ideal Langmuir model



- Simple Langmuir model:
  - Reversible adsorption/desorption
  - Constant & uniform desorption energy, *H*
  - Finite density of identical adsorption sites
- Contamination rate proportional to equilibrium coverage of adsorbed molecules
- Equilibrium coverage expected to saturate with **pressure**, ***p***, due to site competition.

$$\text{C deposition rate} \propto \frac{\boldsymbol{p}}{1+\boldsymbol{p}/\boldsymbol{p}_{Sat}}$$

Initial EUV optics contamination studies (2007)

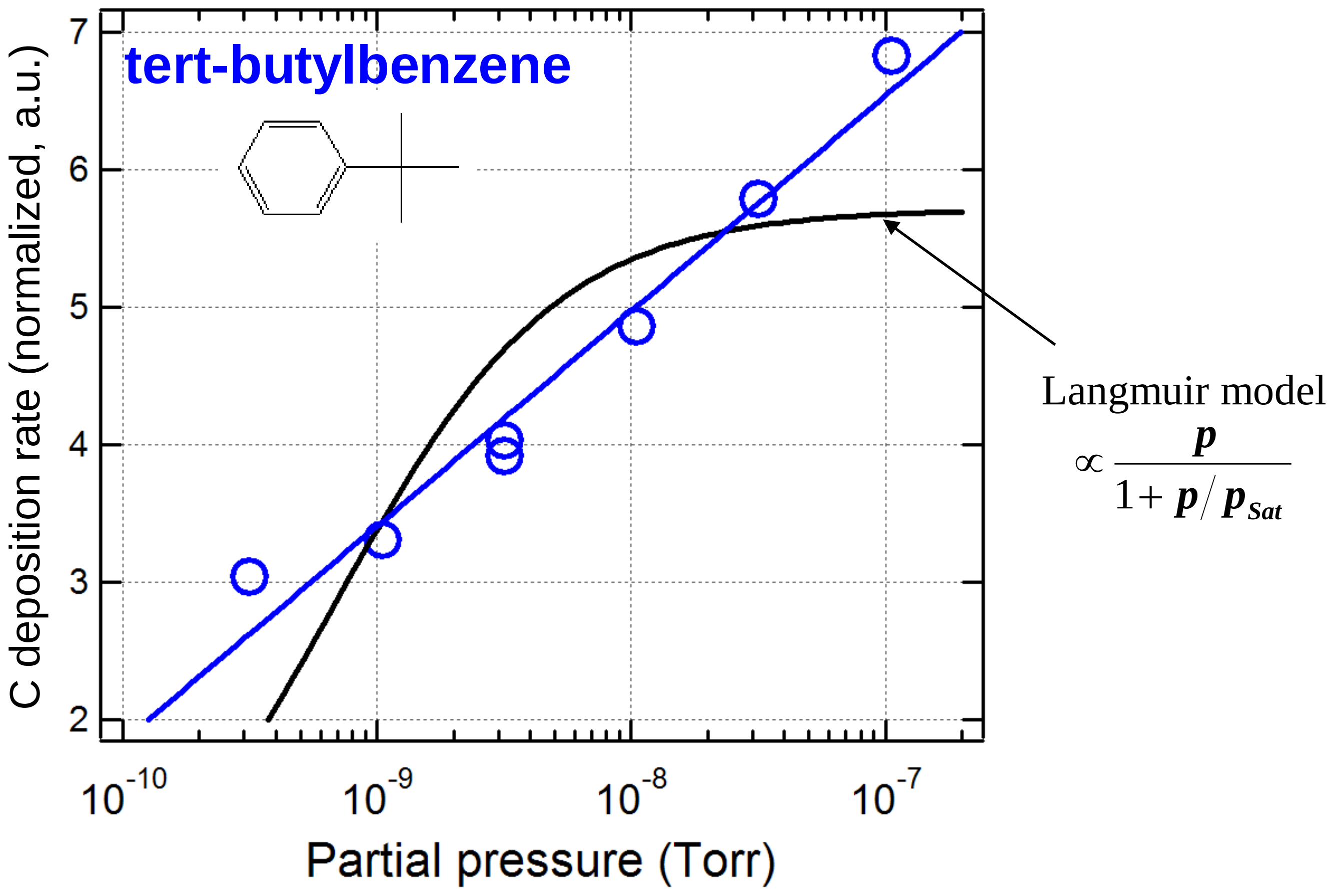


Lines are fits to:

$$\frac{\Delta R}{R} \propto \frac{p}{1 + p / p_{Sat}}$$

- Reflectivity loss of optics after 13 h EUV exposure in methyl methacrylate (MMA) vapor.
- Functional form consistent with Langmuir (saturation),
- But Langmuir fits predict MUCH larger rates than measured.

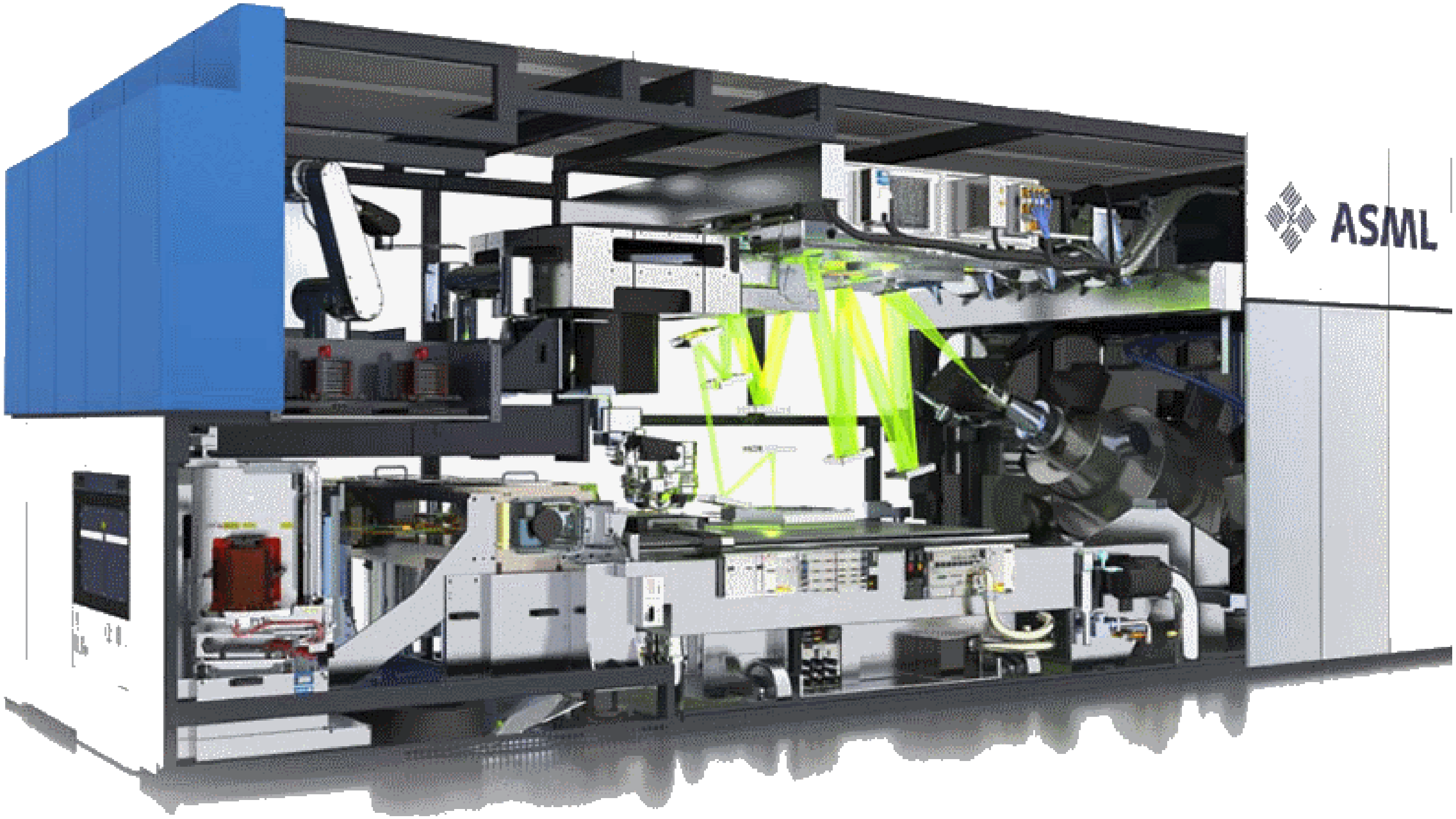
Langmuir model insufficient over large pressure range



- NIST first to report *logarithmic* pressure scaling of contamination rates
- Intel strategy to fund NIST beamline to insure such information is *public*

NIST
National Institute of Standards and Technology

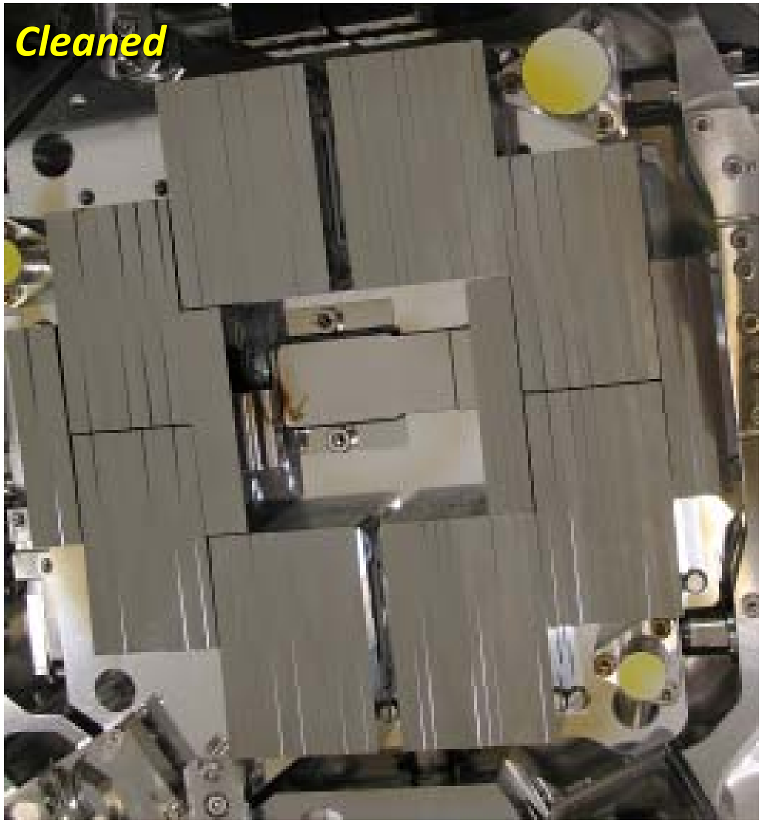
Resist-outgas qualification



- Outgassing from resists could shorten lifetime of tool
- The outgassing potential for all resists must be tested before use in tool
- Determine maximum (worst case) contamination rate for resist by exposing witness plate to EUV intensity $I > I_{sat}$

In situ cleaning: lifetime-productivity tradeoff

Optic assembly in pre-production tool before/after *in situ* cleaning



Images courtesy of ASML

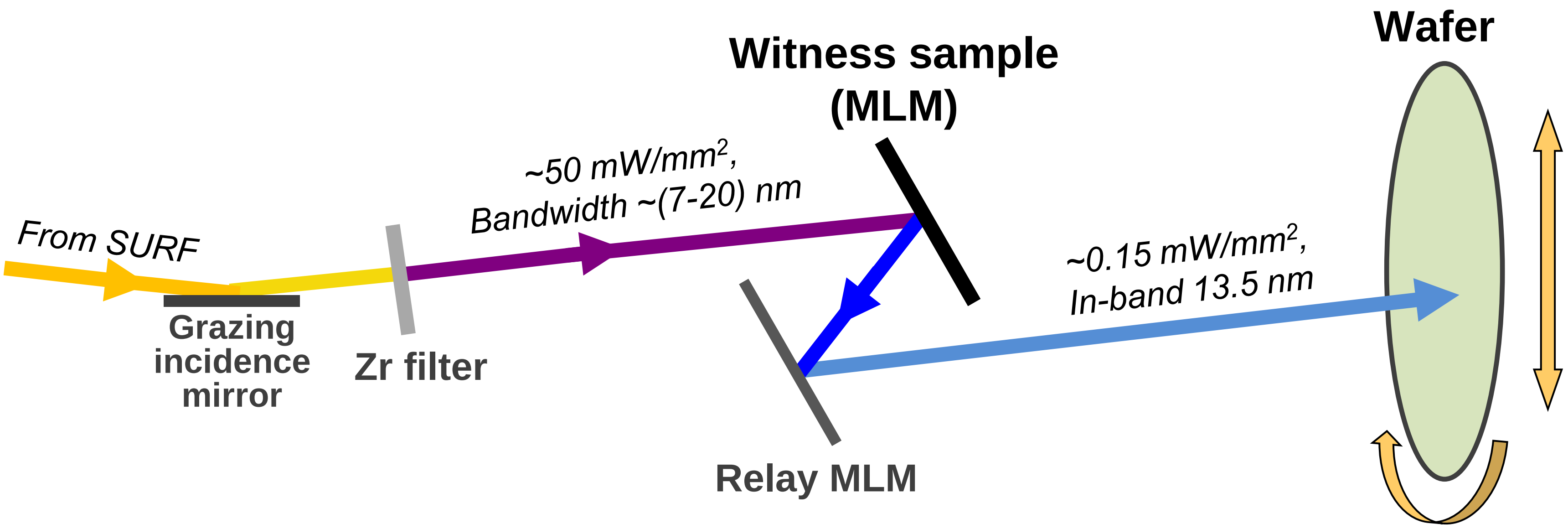
Contamination by outgas from

- Unbaked vacuum chamber
- Components, wires
- Irradiated resist

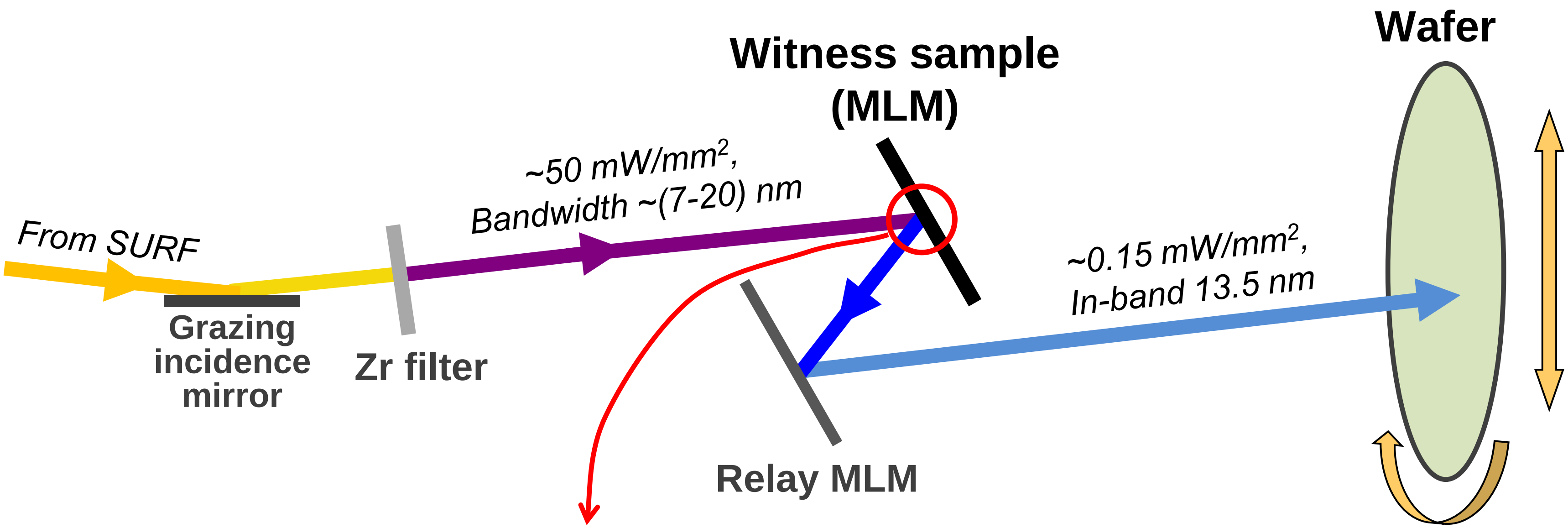
In situ cleaning/mitigation

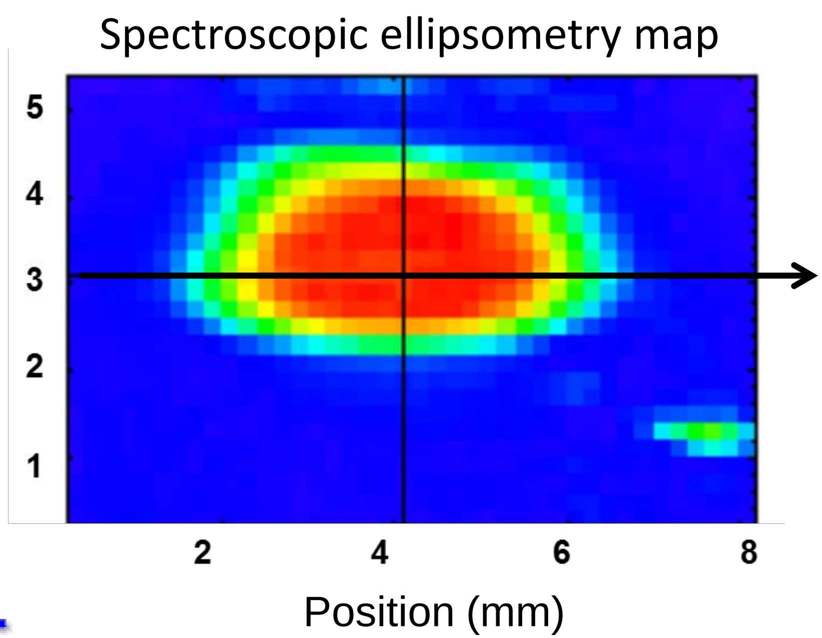
- Extend tool lifetime to required 5 years
- Cleaning time reduces productivity
- Resist development dramatically slowed by outgassing constraints

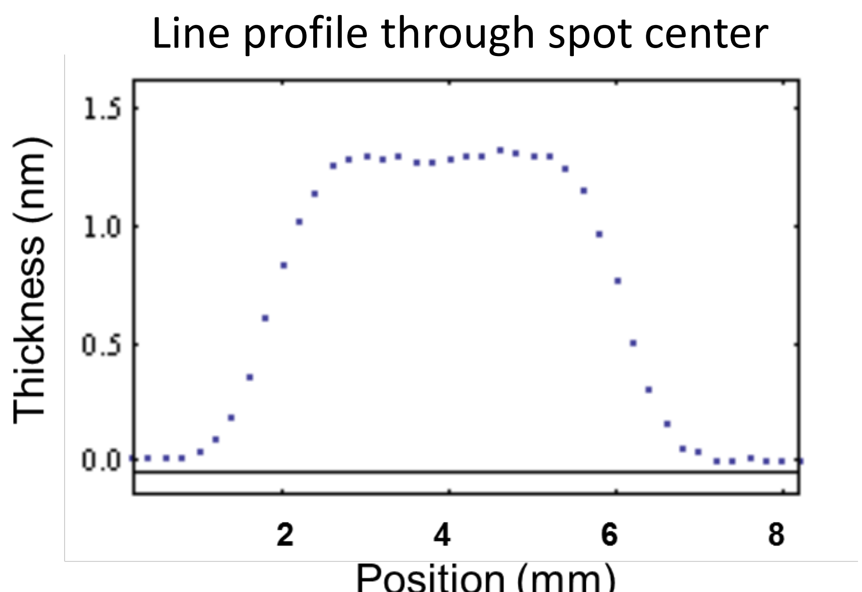
Intensity saturation in resist outgas testing



Intensity saturation in resist outgas testing



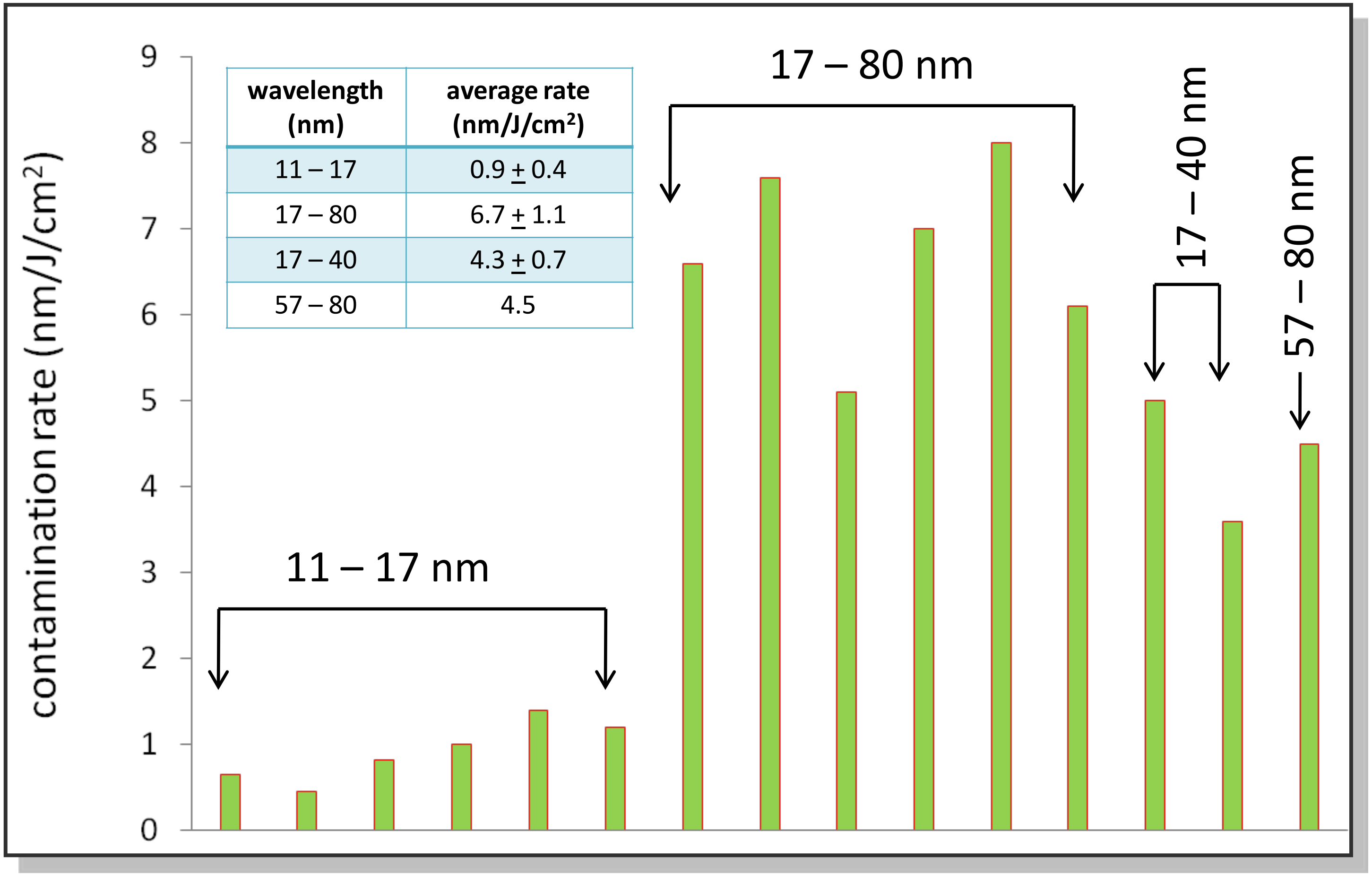




NIST
National Institute of Standards and Technology

Initial wavelength dependence measurements

(Albany: Denbeaux, et al, SPIE 2010)

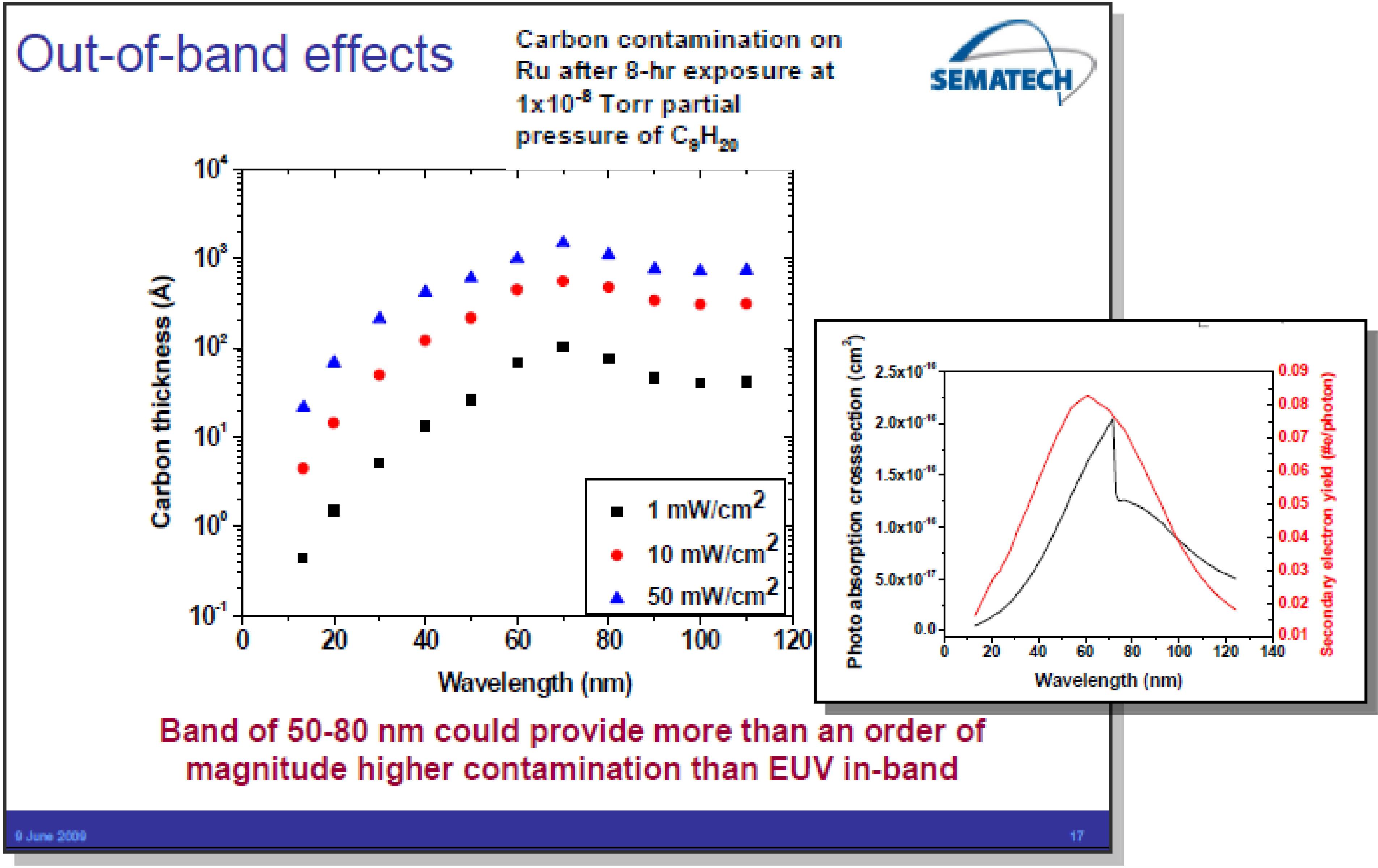


wavelength (nm)	average rate (nm/J/cm²)
11 – 17	0.9 ± 0.4
17 – 80	6.7 ± 1.1
17 – 40	4.3 ± 0.7
57 – 80	4.5

- Comparing rates using broadband source through different filters
- Contamination per unit dose is ~7x higher at wavelengths above 13.5 nm

Calculated wavelength dependence

(SEMATECH: Jindal, SPIE 2009)

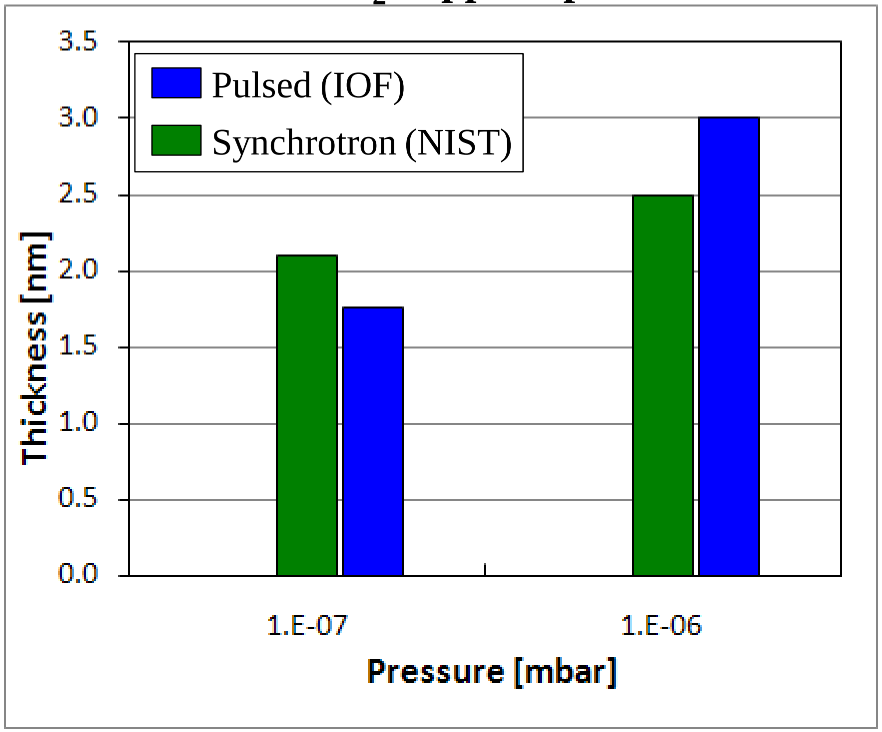


National Institute of Standards and Technology

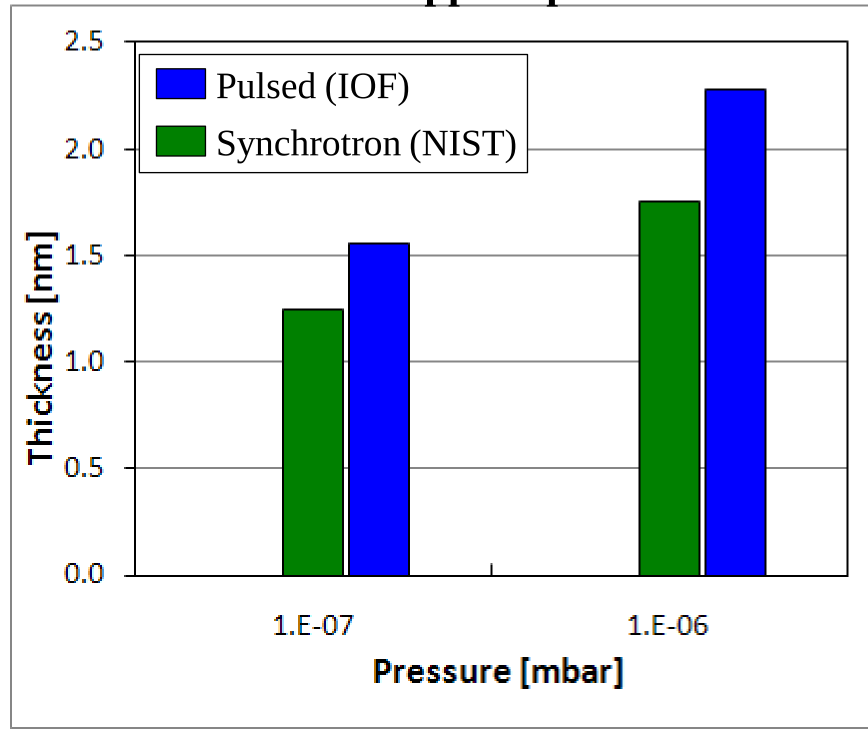
Influence of duty cycle on contamination: pulsed-vs-CW source

(Collaboration with Sergiy Yulin, Fraunhofer Institute IOF, Jena, Germany)

TiO_2-capped optic



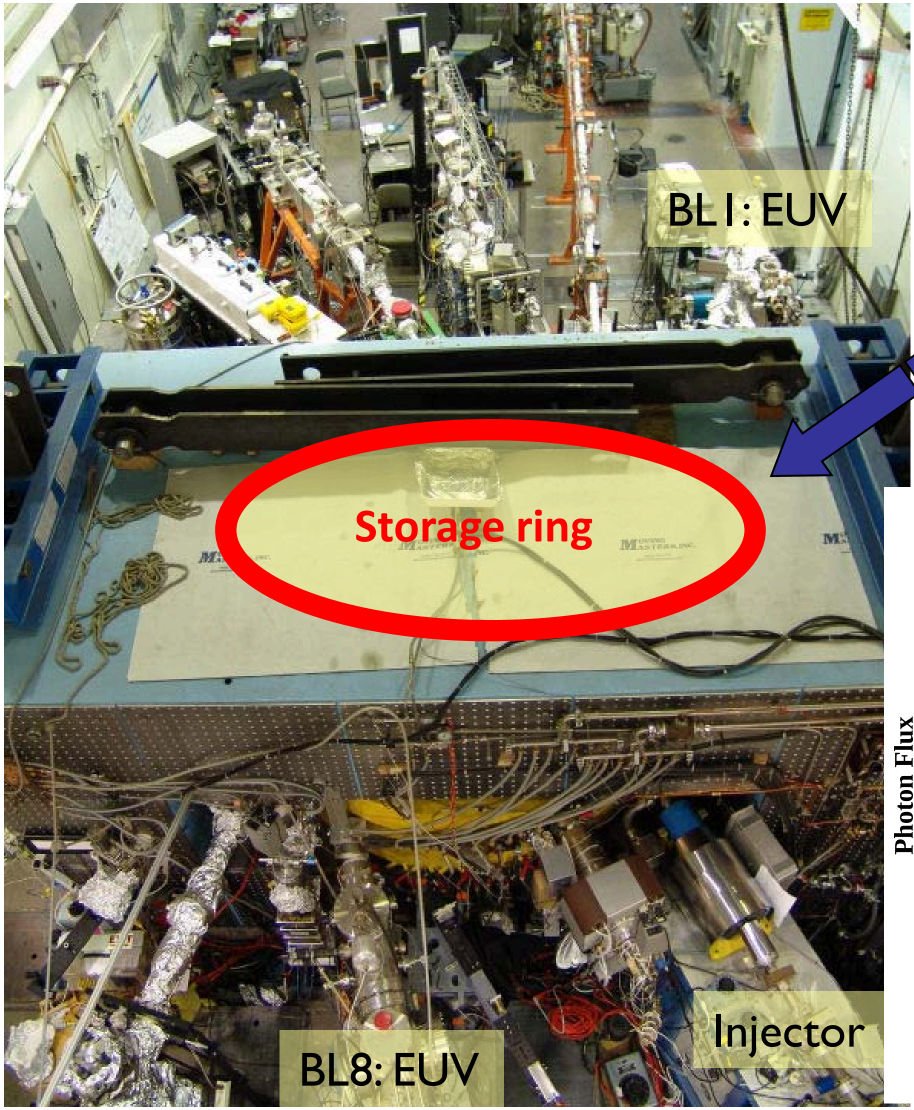
Ru-capped optic



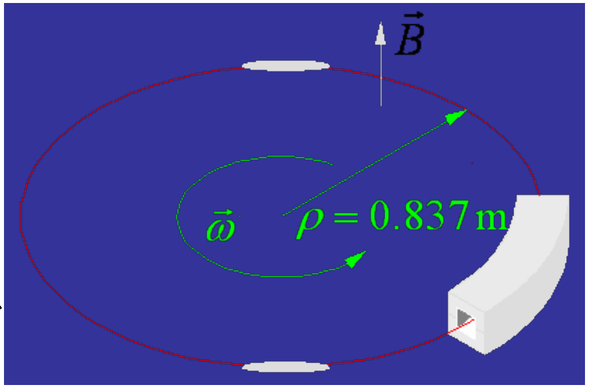
- Identical EUV dose, *average* intensity & pressures of tert-butylbenzene
  - NIST quasi-CW synchrotron: **duty ≈ 0.1** (114 MHz , 1ns pulse width)
  - IOF Xe pulsed plasma: **duty ≈ 6×10^{-4}** (4 kHz , 150 ns pulse width)

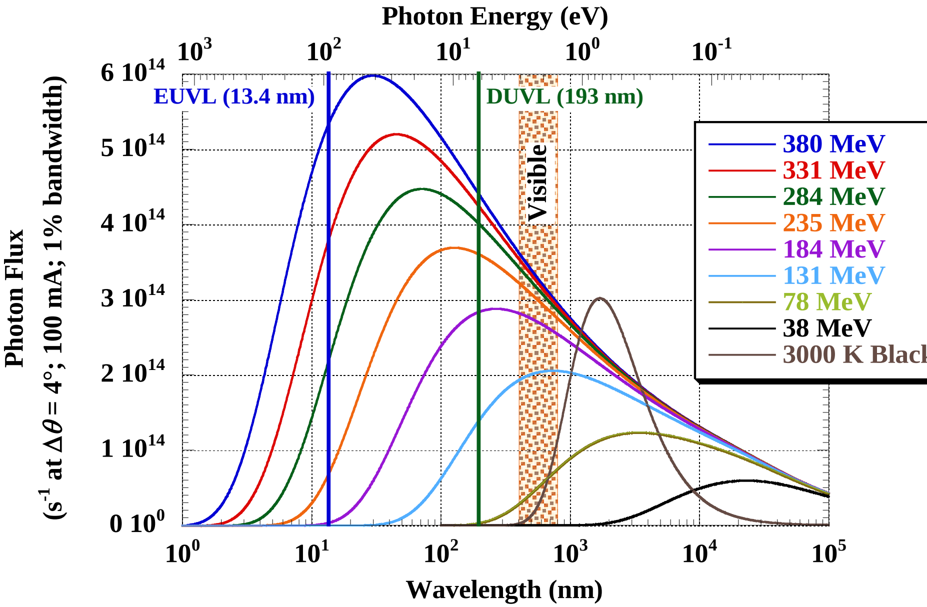
- Deposited C thicknesses similar despite ≈ 170x difference in *peak* EUV intensity

NIST
National Institute of Standards and Technology



Circular storage ring





NIST
National Institute of Standards and Technology

Cleaning of EUV Grown Carbon (BL8)

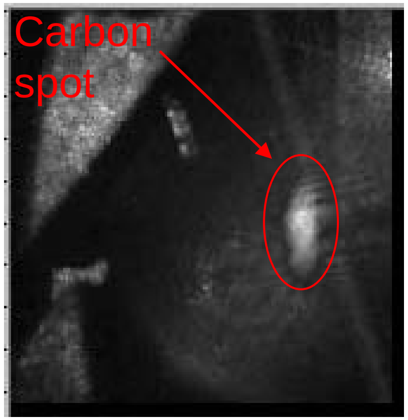
Characterize with in situ null-field ellipsometric imaging system (NEIS) after each step:

1) Deposit ~ 1nm of carbon by EUV exposures

2) Clean using atomic hydrogen *(1 Torr for 12 min)*

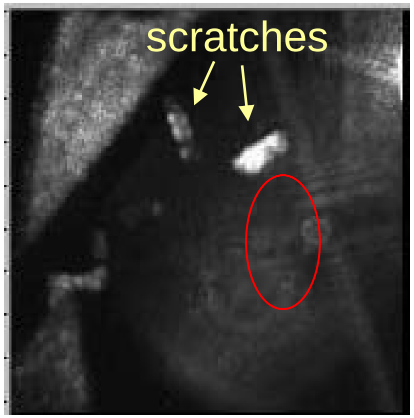
Sequence of NEIS images

1. Deposition:
~1nm of C (EUV grown)



Contamination spot

2. Cleaning with
atomic H



No contamination spot!

- Cleaning rate is at least ≈0.1 nm/min

Cleaning of EUV Grown Carbon (BL8)

Characterize with in situ null-field ellipsometric imaging system (NEIS) after each step:

1) Deposit ~ 1nm of carbon by EUV exposures
2) Clean using atomic hydrogen *(1 Torr for 12 min)*
3) Re-deposit carbon
4) Run cleaner again with N_2 instead of H_2 *(1 Torr for 12 min)*

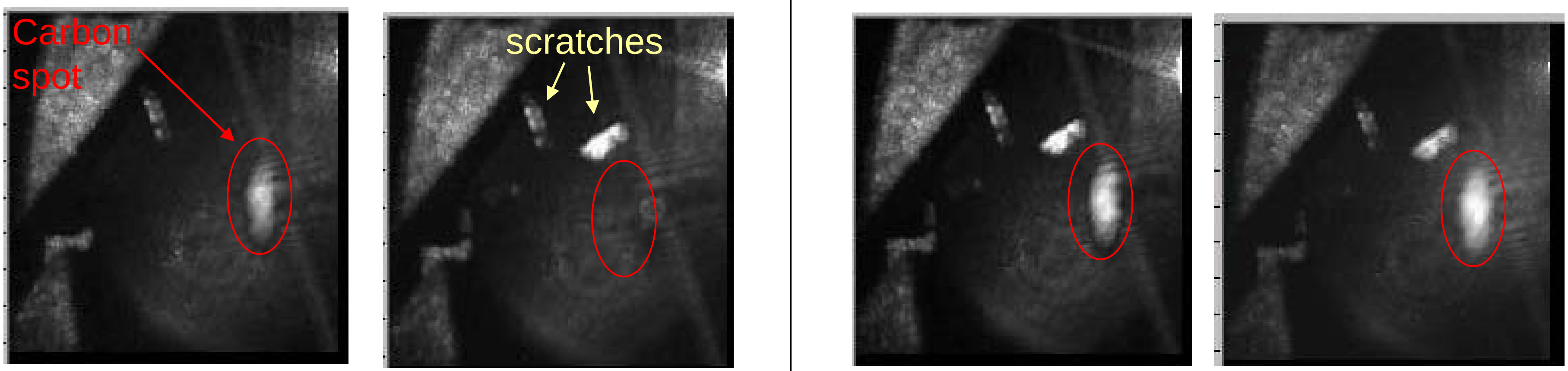
Sequence of NEIS images

1. Deposition: ~1nm of C (EUV grown)

2. Cleaning with **atomic H**

3. Re-deposition: 1 nm of C

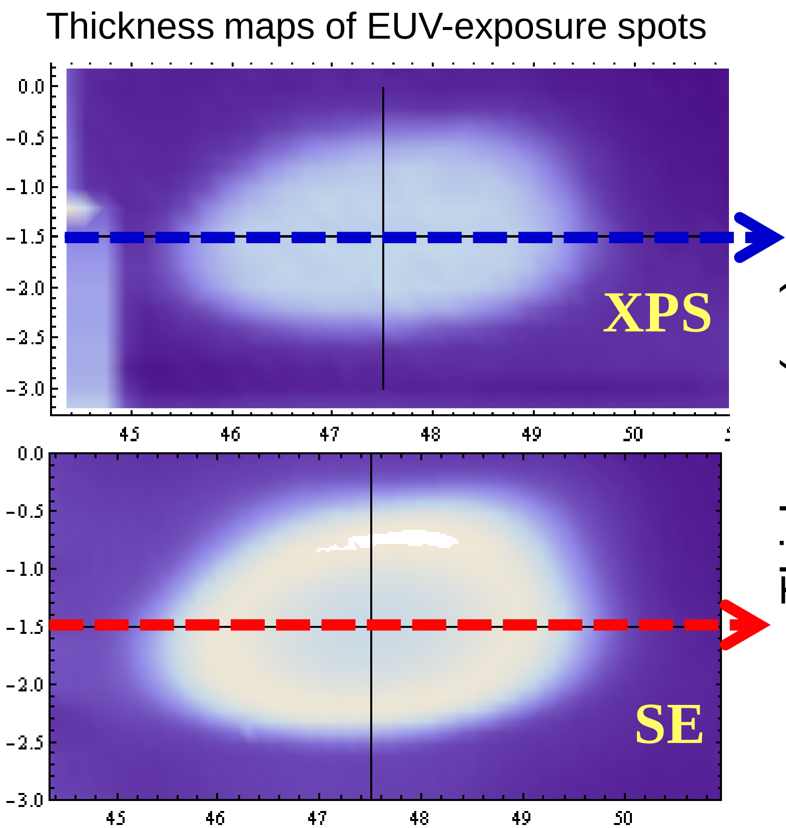
4. Pseudo-cleaning **using N_2 instead of H_2**

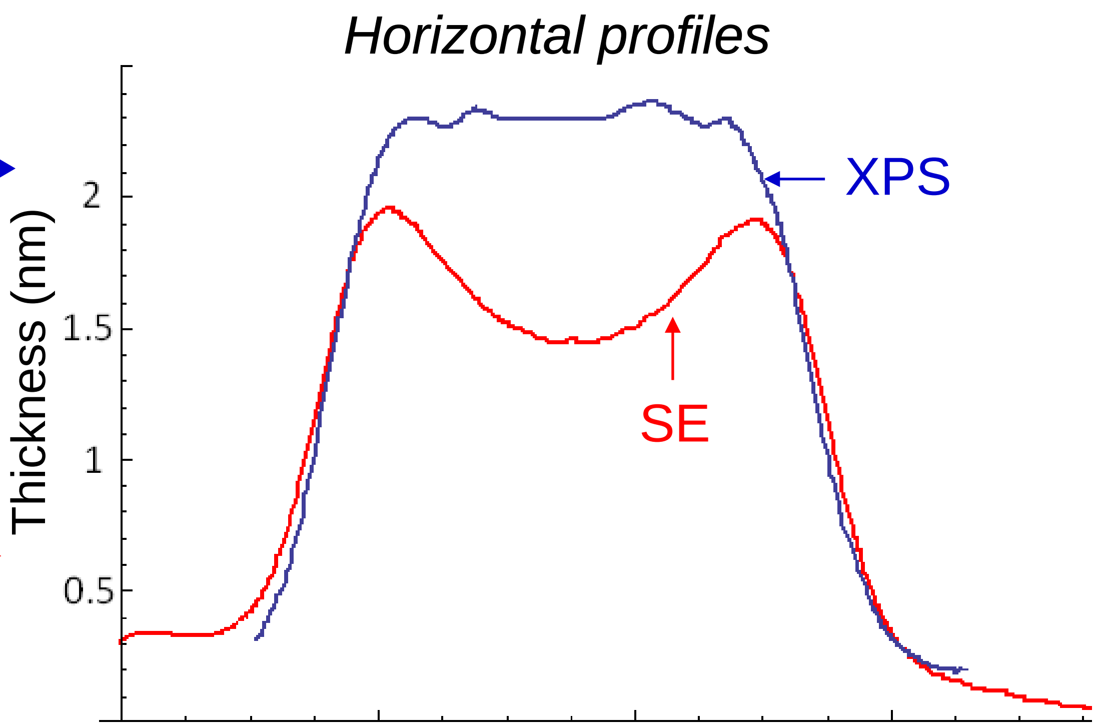


Contamination spot | **No contamination spot!** | Re-contaminate | **Spot unaffected**

- Cleaning rate is at least ≈0.1 nm/min
- 1Torr of H_2 leads to EUV spot removal while 1Torr of N_2 does not remove carbon.

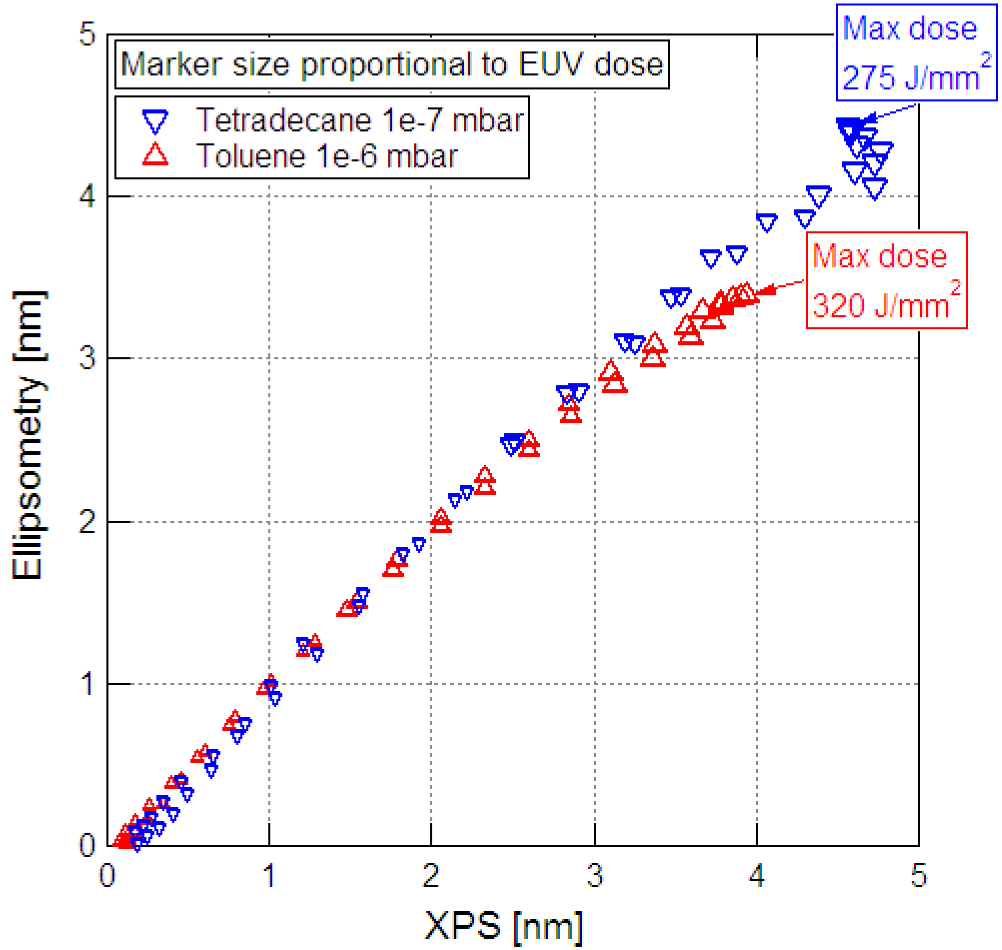
Discrepancy between XPS and spectroscopic ellipsometry





- XPS and spectroscopic ellipsometry (SE) disagree for high-intensity BL-1B exposures.
- Discrepancy largest in high-dose centers of spots.
- Suggests deposited C is altered by prolonged EUV exposure.

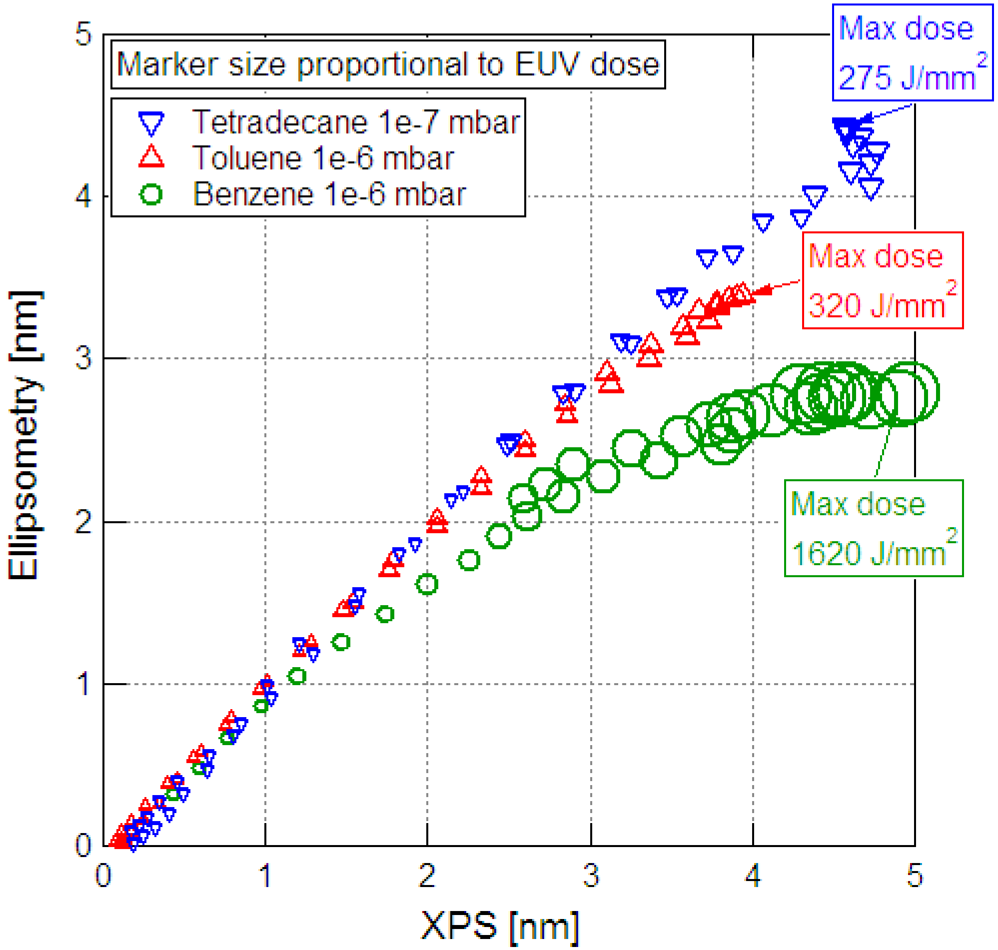
Dose-dependent SE-XPS correlation



- Compare XPS and SE thicknesses at different doses along exposure spot profiles
- Correlation appears good and independent of species for low EUV doses

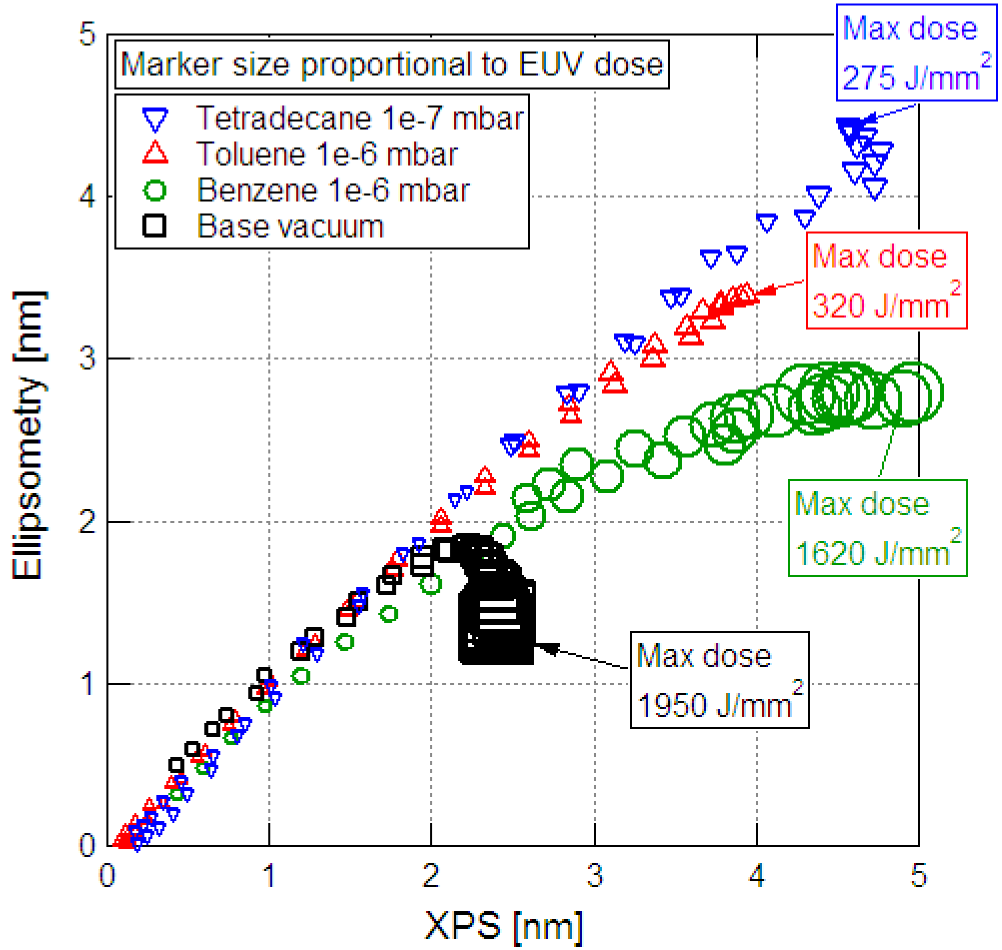
NIST National Institute of Standards and Technology

Dose-dependent SE-XPS correlation



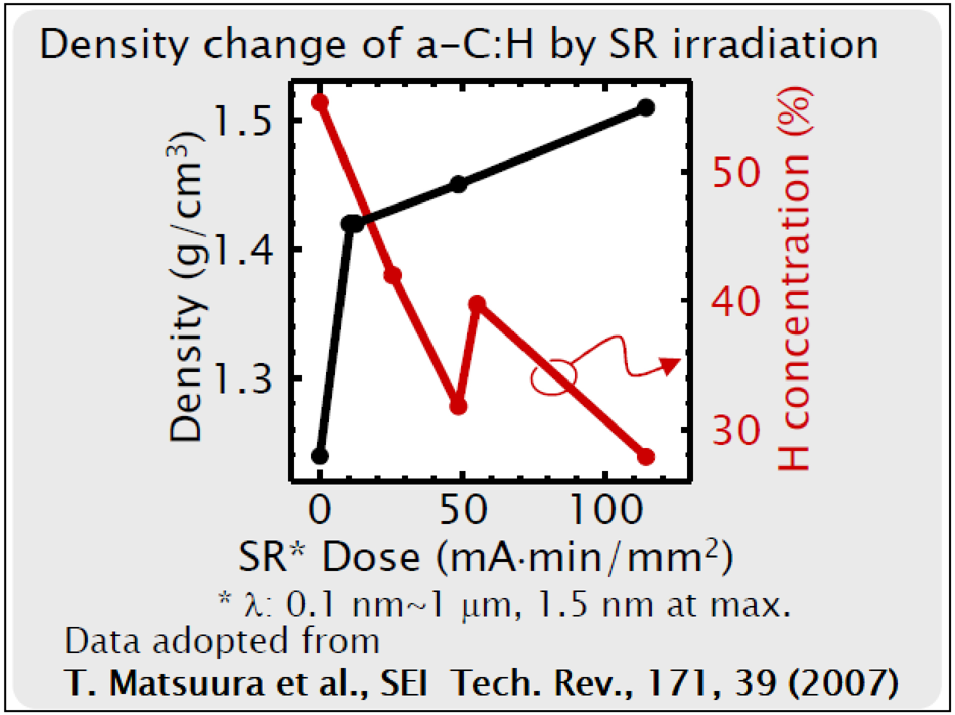
- Compare XPS and SE thicknesses at different doses along exposure spot profiles
- Correlation appears good and independent of species for low EUV doses
- Correlation varies with dose at larger EUV dose exposures

Dose-dependent SE-XPS correlation

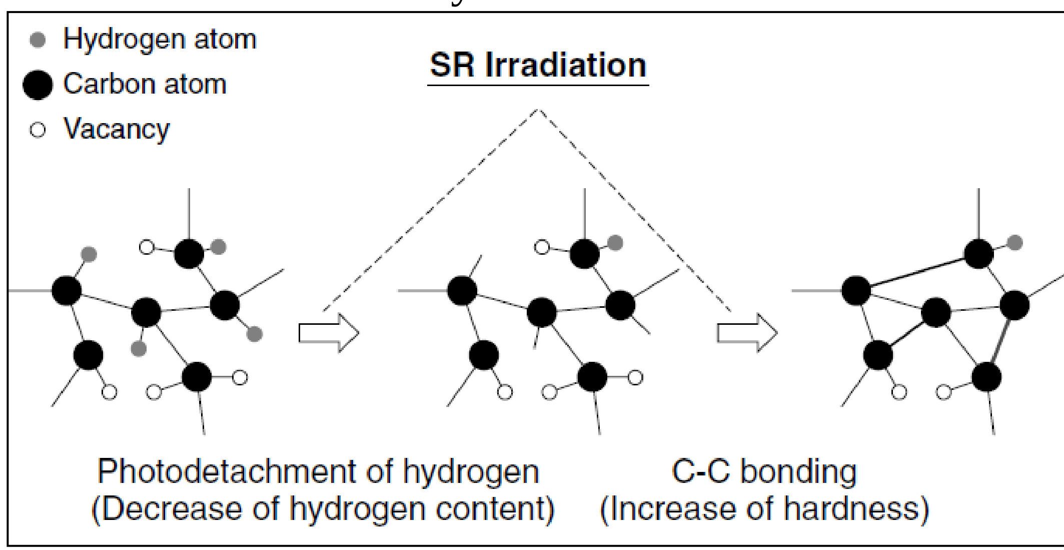


- Compare XPS and SE thicknesses at different doses along exposure spot profiles
- Correlation appears good and independent of species for low EUV doses
- Correlation varies with dose at larger EUV dose exposures
- Dose dependence of correlation highly non-linear at largest doses

Densification of a-C:H films by synchrotron irradiation

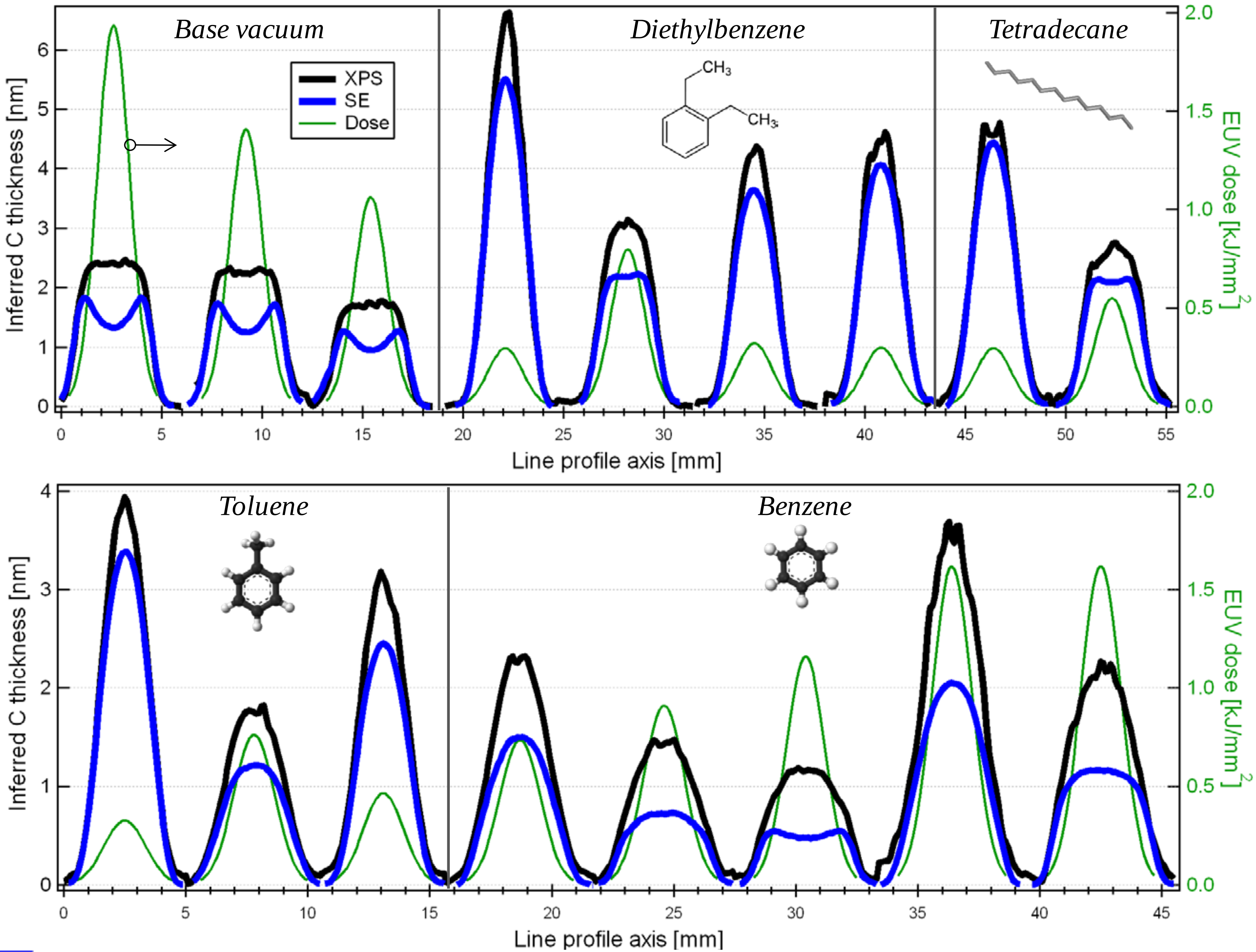


Proposed mechanism: Photodetachment of H followed by formation of new C-C bonds.



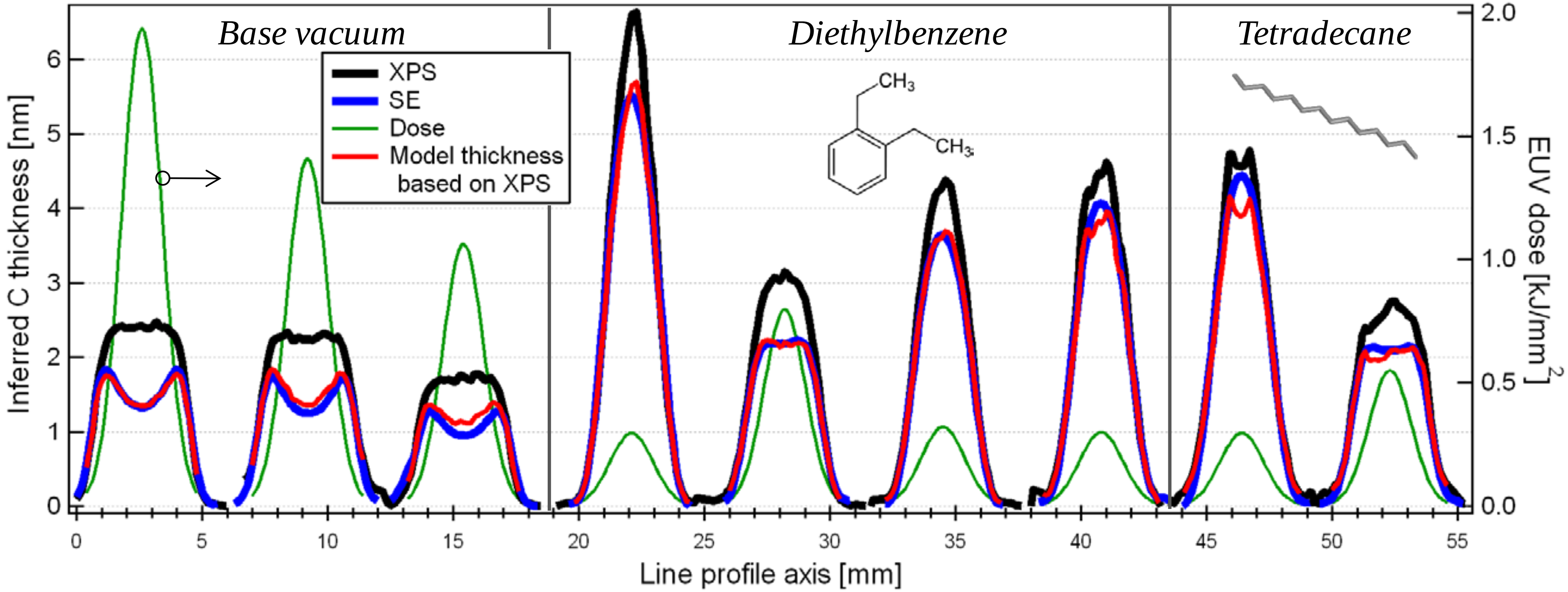
NIST
National Institute of Standards and Technology

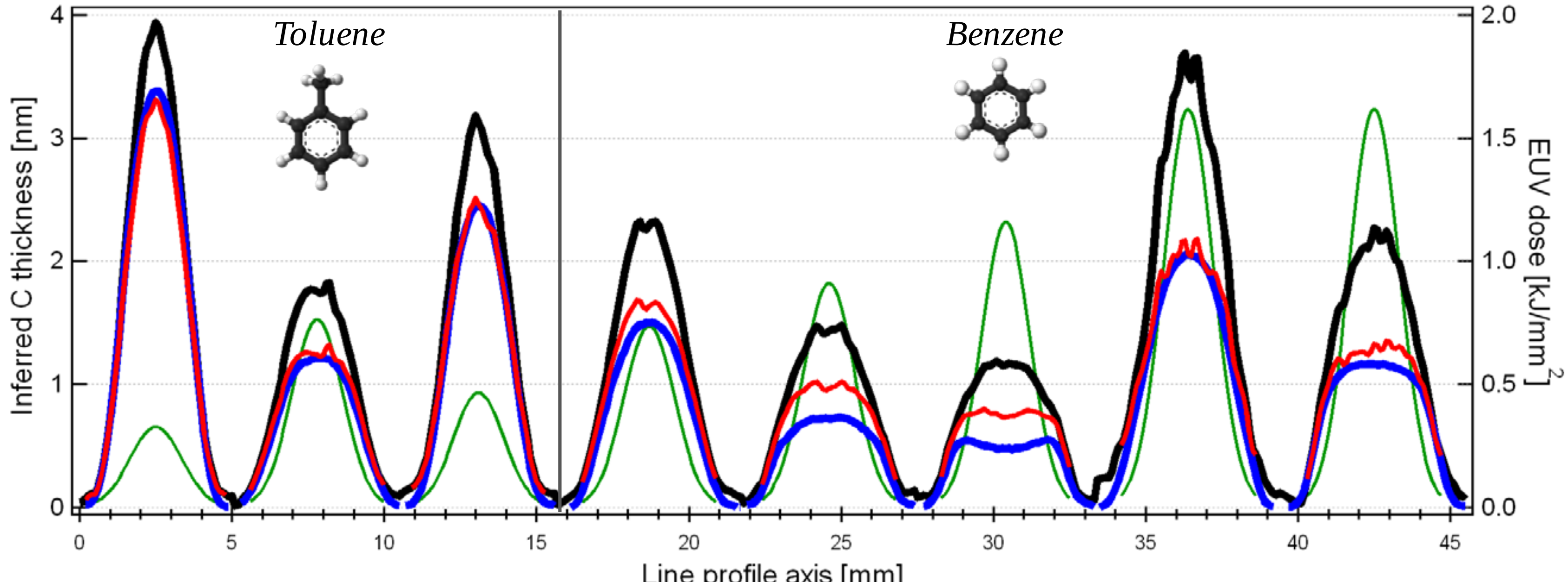
XPS & SE Profiles of Various Exposures



National Institute of Standards and Technology

Fit of dose-dependent XPS-SE correlation to all profiles





National Institute of Standards and Technology